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FLOW AUGMENTING EFFECTS OF ADDITIVES ON OPEN CHANNEL FLOWS

Charles Derick, et al

Columbia Research Corporation

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Environmental Protection Agency

June 1973

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Flow Augmenting Effects of Additives on Open Channel Flows

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17a. Descriptors

*Polymers, *Open Channels, *Flumes, *Fluid Friction, *Water Polution Control, *Weirs, Spillways, Combined Sewers, Non-Newtonian Flow, Turbulent Flow, Flow Augmentation, Flow Measurement, Flow Profiles, Roughness, Slopes, Hydraulic Jump, Reynolds Number, Solutions

17b. Identifiers

*Parshall Flume, *Leopold-Lagco Flume, Injected Concentrations

17c. COSATI Field/Group ~~05B~~ 05G 08B

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FLOW AUGMENTING EFFECTS OF ADDITIVES ON OPEN CHANNEL FLOWS

By

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Kevin Logie

Contract No. 68-01-0168
Project 11020 GQG

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ABSTRACT

Two model open channel configurations (trapezoidal and rectangular) and three water soluble polymers (Polyox Coagulant, Polyox WSR-301, and Separan AP-30) were used to experimentally determine the effects of injecting dilute polymer solutions into open channel water flows.

It was found that for all test cases, injection of the three polymer additives produced flow characteristic changes reflected as either a water surface level decrease at constant flow rates or a flow rate increase at constant static heads. These flow characteristic changes were found to be dependent, in varying degrees, on channel slope, surface roughness, injection point location, polymer injection method, flow Reynolds number, and injected polymer concentration.

In addition, two flumes (Parshall and Leopold-Lagco) and two model side channel spillways (90^{o} V-notch weir and sharp-crested rectangular weir) were used to determine experimentally the effects of polymer additives on the flow measuring characteristics of energy dissipators.

It was found that for specific flow systems, the flumes and spillways could be recalibrated for use with polymer/water flows. However, for the Leopold-Lagco flume and sharp-crested weir, it was found that as the flow increased, the hydraulic jump inherent to these devices was dissipated by polymer injection, thus preventing further recalibration.

This report is submitted in fulfillment of Contract No. 68-01-0168 under sponsorship of the Office of Research and Monitoring, Environmental Protection Agency.

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SECTION 1

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

As a result of data obtained from both a literature search and 3/4-inch pipeline calibration tests, it was determined that three polymers (Polyox Coagulant, Polyox WSR-301, and Separan AP-30) exhibited sufficient "friction reducing" characteristics at low injected concentrations to warrant testing in the model open channel system. Other additives such as Guar Gum were deemed unacceptable for open channel testing, since they produced significantly lower "friction reducing" characteristics at injected concentrations considerably higher than the other three polymers.

Experimental data obtained for two open channel configurations (rectangular and trapezoidal) indicate that a flow augmentation at a constant head, or a water surface level decrease at a constant flow rate, can be obtained in open channels by injecting water soluble friction reducing additives in relatively low concentrations. Maximum flow augmentation is achieved at an injected concentration between 25 wppm and 50 wppm (depending upon the polymer used), and then tends to remain constant or decrease slightly with increased additive concentrations. It should be noted that the flow augmentation values for pipeline flow continue to increase until much larger additive concentrations are reached before leveling off or decreasing.

Theoretical comparison using Prandtl-von Karman's Universal Velocity Distribution Law shows that open channel flows with polymer follows the same trends as pipeline flow and flat plate flow. However, wall shear stress for open channels is somewhat lower than that found for pipeline and flat plate flows at a constant wall shear stress.

For smooth-wall channels, percent flow augmentation tends to decrease as the Reynolds number increases. This may be caused, however, by inadequate polymer mixing with the channel flow. In contrast, for rough-wall channels, flow augmentation is nearly independent of Reynolds number for the same polymer concentrations.

Both Polyox WSR-301 and Polyox Coagulant were found to rapidly degrade when transferred by means of a centrifugal pump. Separan AP-30, however, was not totally degraded by the pumping system. Thus, it may be concluded that this polymer exhibits significant resistance to shear degradation and may be the best candidate material for long channels. Polymer degradation along the length of the model channels was non-existent for the test setup used.

The distance traveled by the polymer additive after injection prior to measuring flow augmentation was found to be significant. Flow augmentation was greater for the polymer injection locations further upstream and decreased as the injection point was moved closer to the measuring stations.

The flume and spillway tests produced two distinct results. The first result shows that if a flume or spillway is used to measure flow, calibration tests must be performed using polymer additives at the specific flow conditions present in the system. The second indicates that either the inherent hydraulic jump of the measuring devices remains within the devices, in which case a calibration curve may be plotted, or the hydraulic jump is dissipated, thus negating the flow measuring capabilities of the device.

A definite trend was established for the flumes and spillways used in this program. As the Reynolds number increases for a specific channel system, the probability of the dissipation of the inherent hydraulic jump within the measuring devices increases. Good calibration was obtained for the Parshall flume, which was actually oversized for the test setup used. It seems feasible to conclude that a solution to the problem of hydraulic jump dissipation for polymer-fluid mediums flowing within flumes or spillways may be to install oversized devices.

RECOMMENDATIONS

Primary on the list of necessary tasks needed to be accomplished before polymers may be used in full-scale open channel systems is obtaining data for channels varying in size between those used for this program and those used in

existing full-scale systems. These data are necessary since no information of this nature has been reported to date by other investigators; in order to establish design criteria to be used for present and future open channel systems using polymer additives, comparison investigations should be performed. Polymer shear degradation along open channel systems should be established.

Economic feasibility studies should be conducted for full-scale open channel systems using polymer additives.

Additional flow measuring device (flumes and spillways) investigations should be conducted to establish whether or not a universal calibration can be made for each device when used for polymer-fluid measurement.

In light of the results of this project, a full-scale open channel demonstration should be conducted and should include both a force-fed and gravity-fed system (see Glossary). The following municipalities have been contacted for said demonstrations.

Fairfax County, Virginia
Monroe County, Rochester, New York
Onondaga County, Syracuse, New York
City of Cleveland, Cleveland, Ohio
City of Balitmore, Baltimore, Maryland
Dauphin County, Harrisburg, Pennsylvania

A "universal" polymer injection system should be developed. This device should include a portability characteristic and an automatic capability. These features would enable municipalities to easily eliminate their overflow problems with a minimum of manpower and initial investment expense.

SECTION II

INTRODUCTION

BACKGROUND

Combined sewer overflows have been recognized throughout the years as major sources of water pollution. Also, sanitary sewer overflows are caused by unlawful residential "tie-ins" to a main sewer system, by unwarranted urban and suburban over-development which results in insufficient sewer line capacities, and/or ground water infiltration through worn or unrepaired older sewer lines. In the past few years, extensive investigation and development programs have been directed toward significant elimination of this pollution problem. From these programs, a number of specific anti-pollution methods have evolved and are now being closely scrutinized and refined for operational use.

One of these methods is injecting high molecular weight polymers into the flow of combined sewer lines at pre-determined concentrations. It is believed that this injection tends to reduce the frictional flow resistance of the waste water. More explicitly, the energy required to drive the waste water can be lowered by polymer injection, and if one assumes a constant energy level, the flow capacity of a given sewer line can be increased. As an added feature of such a method used for increasing older, combined sewer line capacities, it has been demonstrated that no additional stress due to fluid pressure is transmitted to these lines when their capacities are increased. Such a feature has been welcomed, since many of the older lines would need costly repairs if other flow augmentation methods were employed.

The techniques of polymer injection and the corresponding theory associated with this phenomenon have been reported by many investigators for completely filled conduits and for flow over flat plates. Most of those investigations have been performed as laboratory experiments, with a few being performed in full-scale sewer line systems (Refs. 1, 2, and 3). Unfortunately, only a limited number of investigations have been reported concerning open channel applications,

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and these are directed toward partially filled circular channel configurations.

This report describes and presents the results of an Environmental Protection Agency sponsored research project which investigated and demonstrated the effect of polymer additives on model open channel flows.

PURPOSE

The primary purpose of this project was to experimentally determine the flow augmentation effects of water-soluble polymers on the flow of water within different model open channel configurations, and on energy dissipators such as flumes and side-channel spillways used as flow measuring devices.

In addition, secondary purposes included investigating polymer insertion methods, evaluating polymer degradation resistance as a function of insertion point location, and determining flow augmentation effects of polymer additives as a function of channel slope, wall roughness, and polymer type. A theoretical analysis for polymer flow in the open channels using Prandtl-von Karman's Law of the Wall and Velocity Defect Law was also performed in order to correlate the experimentally determined open channel data with data of previous investigations for flow in completely filled pipelines and on flat plates.

SCOPE

The work performed for this project was essentially separated into two tasks which were conducted concurrently. The first task was composed of both a theoretical analysis and a comprehensive literature search. The second task consisted of performing, in a laboratory atmosphere, the experimental open channel tests.

Initially, all known references concerning polymer additive effects on fluid flow within pipelines, within open channels, and over flat plates were gathered and reviewed for

applicability to the investigation. Based upon these data, a theoretical analysis was conducted using the Prandtl-von Karman Universal Velocity Distribution Law. This theory is utilized to predict velocity profile characteristics of flow in pipelines, flat plates, and open channels as a function of the wall shear stress and distance from the wall.

Experimental tests and evaluations were conducted in accordance with test plans (Refs. 4 and 5) prepared in the beginning of the project by Columbia Research Corporation and approved by the cognizant EPA project officer.

Open channel tests were conducted, using two channel configurations; rectangular and trapezoidal. Data were taken for each of these configurations for three types of polymers at two Reynolds numbers, three channel slopes, two channel roughness levels, and two polymer solution concentrations. In addition, polymer injection methods and injection point locations were studied and evaluated for use with the particular model test system.

Flume and spillway tests were performed, using the open channel configurations mentioned above. Two flumes -- Parshall and Leopold-Lagco -- and two side-channel spillways (weirs) -- 90° V-notch and sharp-crested rectangular -- were investigated and calibrated with and without polymer injection. These tests were conducted using one polymer additive (found to have the greatest flow augmentation effect in the open channel configurations) and two channel slopes.

SECTION III

POLYMER SELECTION

LITERATURE SEARCH

Prior to performing experimental open channel tests, it was necessary to conduct an extensive literature survey (Appendix 1). This survey consisted primarily of gathering theoretical and experimental data pertinent to the friction reducing capabilities of known water-soluble polymers. Emphasis was placed on locating correlation data between pipeline/flat plate flow and on data for open channel flow systems. The results of this search indicated that little information has been recorded outlining correlation procedures for use when comparing the effects of polymer additives on the water flow within pipelines to that of the flow over flat plates. In addition, it was found that polymer data for open channel flow systems have been scantily reported and pertain exclusively to semicircular channels or partially filled pipelines.

Based upon this literature search and available information supplied by polymer manufacturers, it was verified that the four original polymer additive types specified in the work statement of this project were superior to all other polymers as friction reducing additives for water flow. In light of this, it was decided that all testing efforts should be directed toward using only these four polymers.

THREE-QUARTER INCH PIPELINE CALIBRATION TESTS

Experimental Test Arrangement

The experimental setup used for the 3/4-inch pipeline calibration tests is shown in Figure 1. This test arrangement included the following equipment:

Component	Specification
Centrifugal water circulating pump	20 gpm
Variable displacement polymer feed pump	0 - 0.055 gpm

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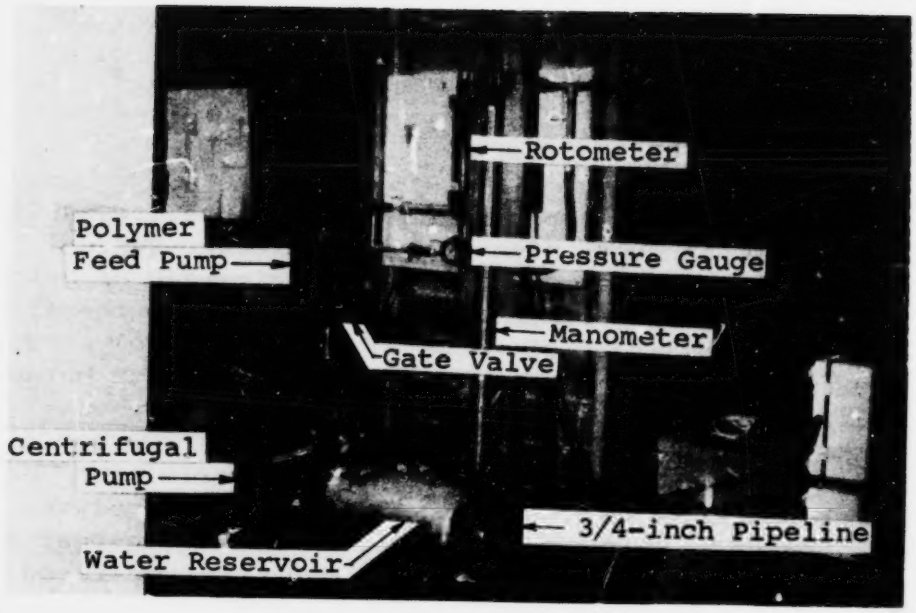


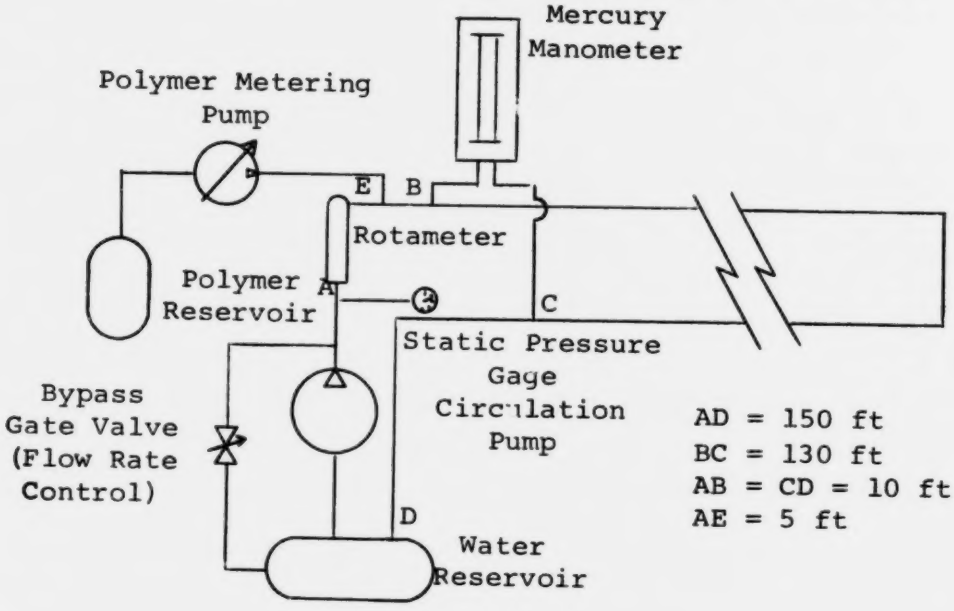


FIGURE 1. EXPERIMENTAL 3/4-INCH PIPELINE POLYMER CALIBRATION TEST SET-UP

Component	Specification
Bourdon-tube pressure gauge	0 - 100 psig
Rotometer	2.4 - 30 gpm
Manometer, mercury	100 in.
3/4-inch pipeline	150 ft
Steel tank (water reservoir)	12 gal.

During operation, the water was pumped by a Rivett centrifugal pump from a reservoir (steel tank) through a Fischer-Porter rotometer into 150 feet of 3/4-inch nominal I.D. pipeline back into the reservoir. A gate valve located at the pump outlet was used to control the flow rates by diverting excess flow through a bypass circuit.

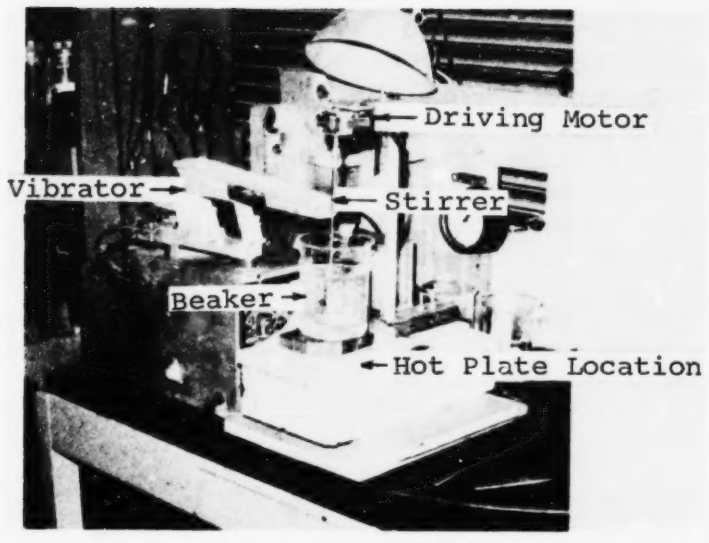
Preparation of Polymer Solutions

The four different polymer products listed herein were initially supplied in powder form and had to be prepared as a solution prior to testing.

Manufacturer	Polymer Resin
Union Carbide Corporation	Polyox WSR-301 (Polyethylene Oxide)
	Polyox Coagulant (Polyethylene Oxide)
Dow Chemical U.S.A.	Separan AP-30 (Acrylamide)
Stein, Hall & Company, Inc.	Jaguar Guar Gum (Polysaccharide)

The polymer solutions were initially prepared using the mixing apparatus of Figure 2. Three different techniques were employed for mixing these solutions, depending on the polymer type and the concentration of the solution.

The first technique employed a vibrator to feed the polymer in powdered form into a 1,000-milliliter beaker of tap water stirred at approximately 300 rpm. As the solution became more viscous, the rotational speed of the agitator was reduced to approximately 100 rpm. The stirring was continued until all of the powder was dissolved and the solution reached a homogeneous state. This process was



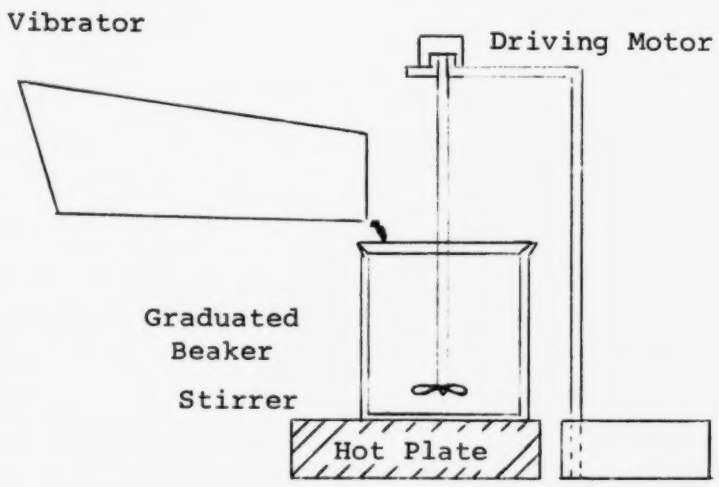


FIGURE 2. POLYMER SOLUTION MIXING DEVICE
(3/4-INCH PIPELINE TESTS)

used in the preparation of solutions of Separan AP-30 and low concentration (0.1%) solutions of Polyox Coagulant and Polyox WSR-301.

Guar Gum solutions were prepared using a similar technique. Since it was found that Guar Gum is readily soluble in water, the vibrator was not required. The Guar Gum powder was transferred from a strip of waxed paper into a beaker of tap water under brisk agitation. As in the first technique, the agitation was continued until the powder was completely dissolved.

When mixing the more concentrated (1.0% and 0.5%) solutions of Polyox Coagulant and Polyox WSR-301, homogeneous solutions were difficult to obtain using the above techniques. Thus, an alternate approach was used. A weighed sample of Polyox was added to a beaker of boiling water so that a good polymer dispersion could be obtained. Note that although both Polyox WSR-301 and Polyox Coagulant are insoluble in boiling water, the increased temperature has no effect on their potency as a friction reducing additive. Room temperature water was then added, the heat source was removed, and the stirring was continued until the solution reached a uniform state. At this time, the solution was placed in a cold water bath and allowed to cool to room temperature.

Polymer Injection Procedure

All polymer solutions were introduced into the 3/4-inch pipeline flow downstream of the centrifugal pump by means of a Meco-O-Matic chemical solution feeder pump. This pump had the capability of varying the polymer feed rate to compensate for the flow in the 3/4-inch pipeline in order to achieve the desired concentration levels.

Experimental Test Procedures

In order to evaluate the effectiveness of each of the four polymer additives mentioned above, calibration tests were performed.

The flow performance of each additive was rated in terms of the flow increase that it produced at a constant head loss (the head loss being the differential pressure measured across 130 feet of pipeline). The data necessary for this rating was obtained as follows.

The first step established base data using tap water alone. An initial flow rate was set, and the corresponding head loss and pump discharge pressure were measured with the manometer and the pressure gauge, respectively. Once this information was recorded, the feed pump was brought on line, and a polymer solution was injected into the pipeline flow. The injection resulted in a subsequent decrease in both the head loss and the discharge pressure. In order to return the head loss to its original value, it was necessary to increase the flow through the pipeline by closing the bypass valve. The new flow rate was measured with the rotometer and recorded. It was then compared to the initial flow rate using Equation (1) of Appendix 2.

By changing the polymer injection rate and repeating the above procedure for the same initial pipeline flow, the flow augmentation was expressed as a function of the polymer concentration.

The polymer injection rate was varied in two ways -- by changing the feed pump setting, and by changing the intial concentration of the polymer solution. Three different initial polymer solutions (.1%, .5%, and 1%) and four different pump settings were used. This made it possible to obtain at least 12 data points for each polymer additive.

To determine the injected polymer concentration in the pipeline flow, Equation (2) of Appendix 2 was used. The volumetric rate of injection "q_i", was determined using a graduated beaker and a stopwatch, and the time required to inject 100 milliliters was measured and recorded. All of the other variables in Equation (2) were either known or easily computed from the recorded data.

The entire test procedure was repeated for three different initial pipeline flow rates to insure that the relative effectiveness of each of the polymers was the same over a range of Reynolds numbers.

Calibration Test Results

In order to illustrate the effectiveness of the polymer additives in the 3/4-inch pipeline flow, two typical methods of graphical representation have been used. The first method plots the experimentally determined flow augmentation against injected polymer concentration for three different flow Reynolds numbers. In addition, three different percent solutions were used for each polymer tested thus permitting the maximum injected polymer concentrations to be obtained with the available test setup. The results using this method are shown in Figures 3, 4, and 5. Comparing the data on these figures, it is seen that Polyox Coagulant and Polyox WSR-301 display approximately equal effectiveness, followed by Separan AP-30 and Guar Gum. For the polymer concentrations and the minimum and maximum Reynolds numbers tested, Guar Gum produces a negligible effect on the pipeline flow, compared to the other three polymers. Thus, it was decided to discontinue testing with this polymer. It is also clear that as the Reynolds number increases, the polymer effectiveness increases and, for the injected polymer concentrations tested, the effectiveness continues to increase for constant Reynolds number.

The second method compares the pressure drop versus pipeline flow rate data of undosed tap water against the pressure drop at constant injected polymer concentration for water/polymer flow. Such a method has been used successfully as a check on the experimentally determined flow augmentation data previously mentioned. As shown in Figure 6, the derived flow augmentation for Polyox WSR-301 at a polymer concentration of 12.4 wppm is approximately 72%. This value corresponds closely to the experimentally determined flow augmentation percentage found on Figure 4.

In addition, the results presented above were used to calibrate the polymer solutions used for the open channel testing. This was done simply by repeating the pipeline tests for each new polymer solution. Thus, the solutions were mixed until the data on Figures 3, 4, or 5 were duplicated, thereby insuring a known polymer solution concentration.

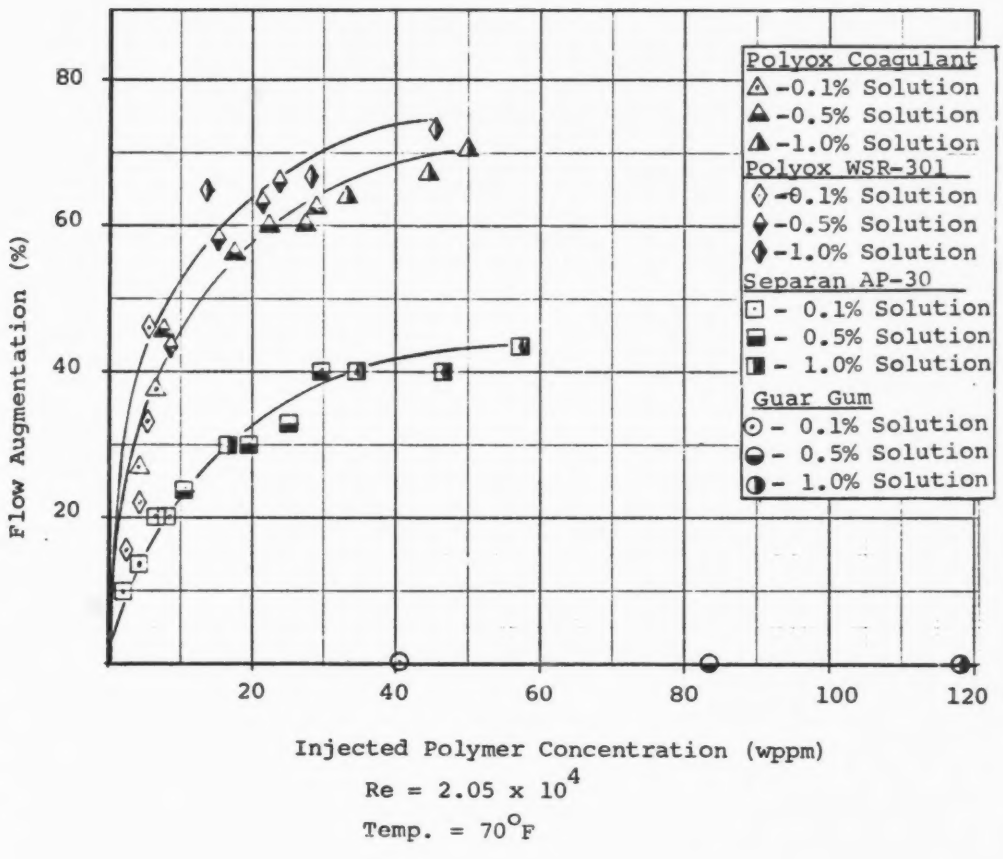


FIGURE 3. POLYMER PERFORMANCE CURVES
(3/4-INCH PIPELINE TESTS)

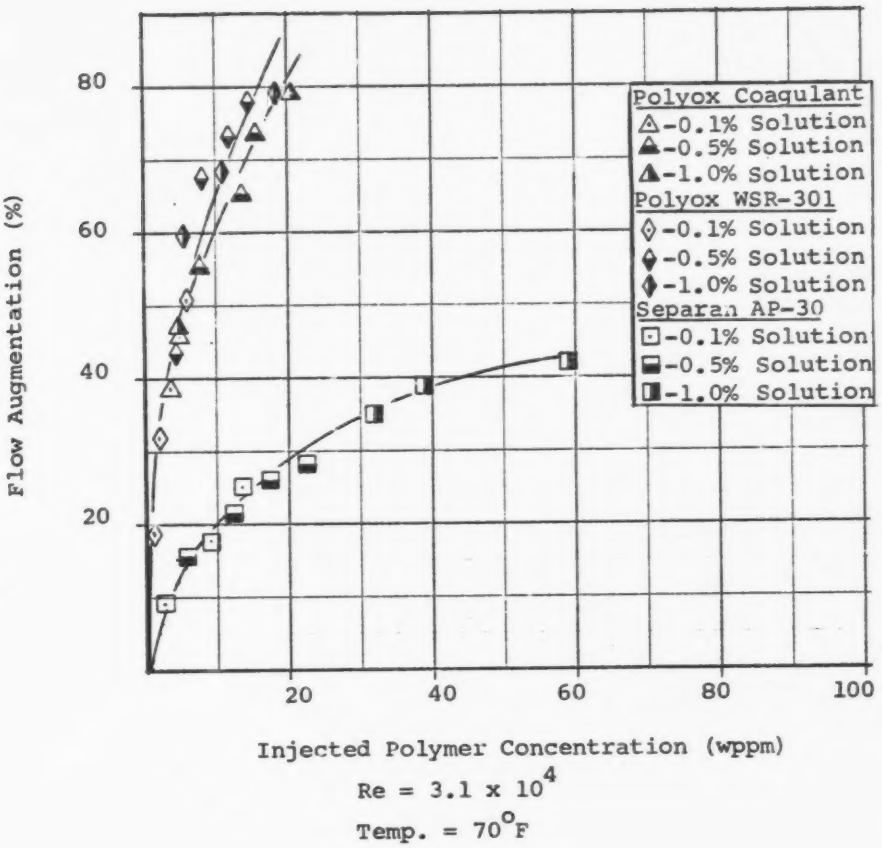
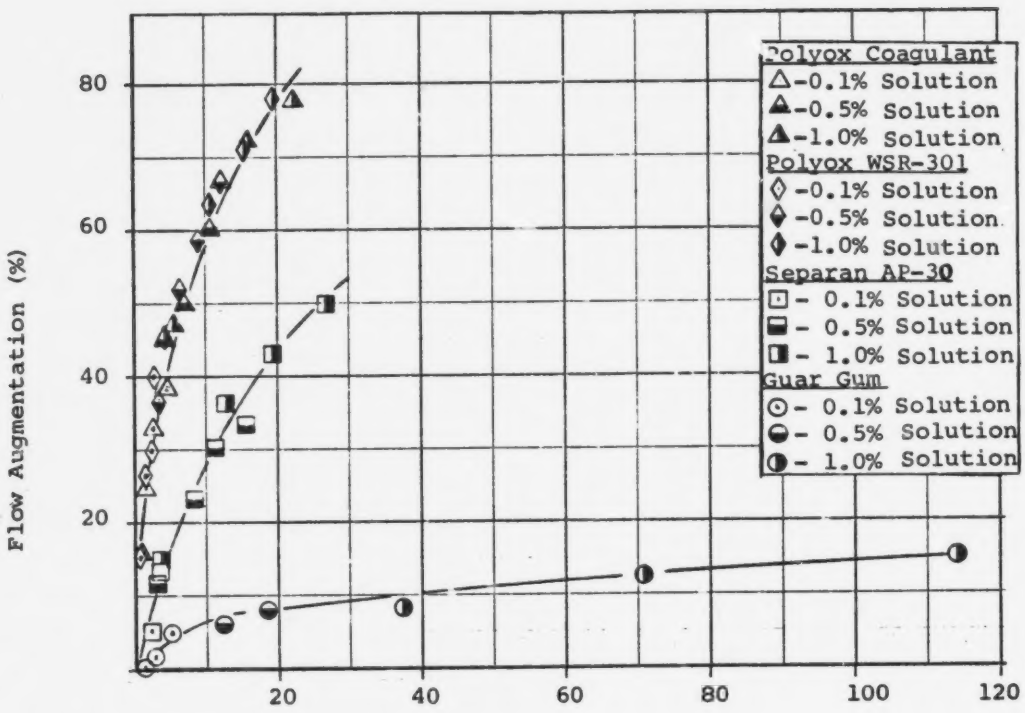


FIGURE 4. POLYMER PERFORMANCE CURVES
(3/4-INCH PIPELINE TESTS)



$Re = 4.1 \times 10^4$

Temp. = $70^{\circ}F$

FIGURE 5. POLYMER PERFORMANCE CURVES
(3/4-INCH PIPELINE TESTS)

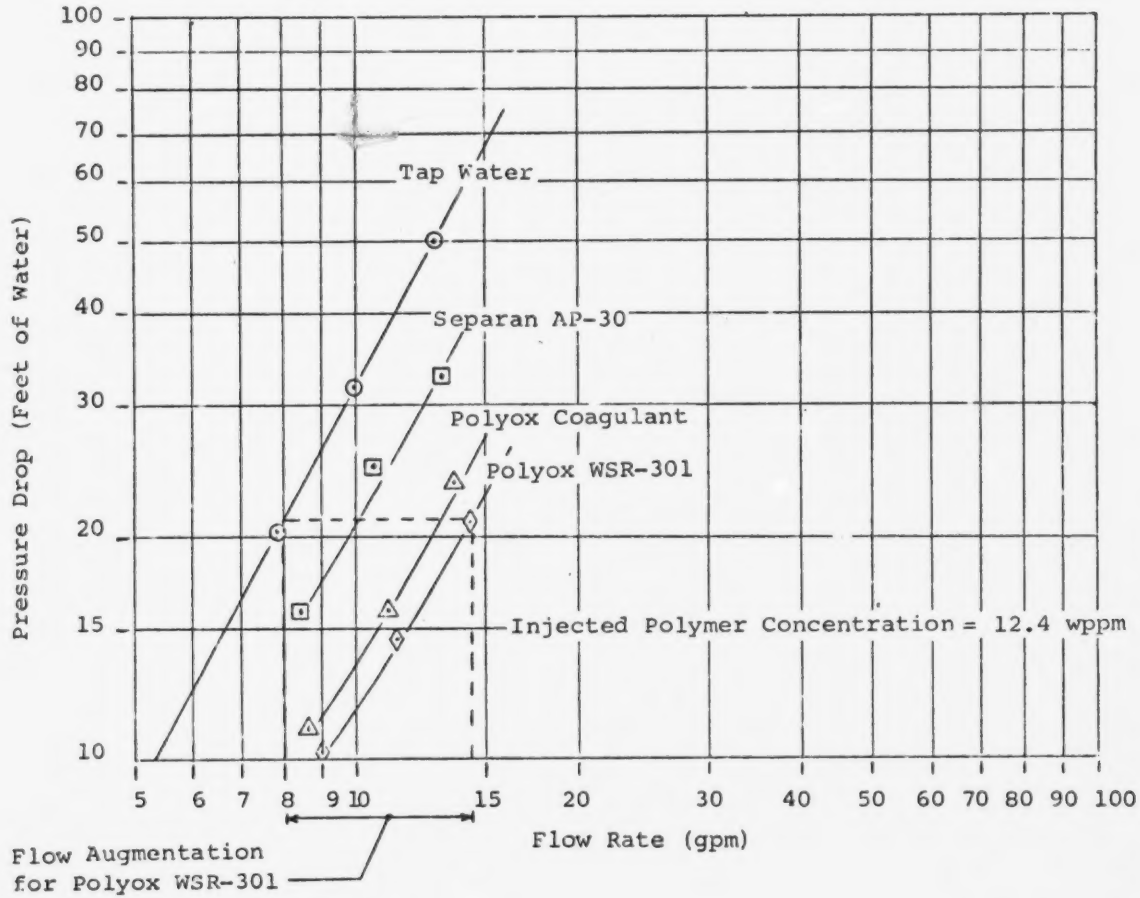


FIGURE 6. POLYMER EFFECTIVENESS CURVES (3/4-INCH PIPELINE TESTS)

SECTION IV

OPEN CHANNEL FLOW EVALUATION

EXPERIMENTAL TESTS

Test Arrangement

The general layout of the open channel test facility is shown in Figure 7. Two different model channel configurations were used for testing -- rectangular, and trapezoidal. Both channels were fabricated from 60 feet of 1/16-inch sheet steel. The first 20 feet of the channels were used to ensure that uniform turbulent flow was developed, and the remaining 40 feet were used for the test section. The channels were supported by five supports which could be adjusted to obtain slopes of 0%, 1%, 2%, 3%, and 4%. Channel surfaces were initially painted with an epoxy paint to give a smooth finish, and were then roughened by repainting with a sand and paint mixture. Specifications for each channel configuration are listed below.

1. Rectangular

Bottom width	6 in.
Side length	6 in.
Channel length	60 in.
Manning factor	
(a) Smooth surface	.009
(b) Rough surface	.013

2. Trapezoidal

Bottom width	5 in.
Side length	6 in.
Channel length	60 ft.
Interior angle	60^{o}
Manning factor	
(a) Smooth surface	.009
(b) Rough surface	.013

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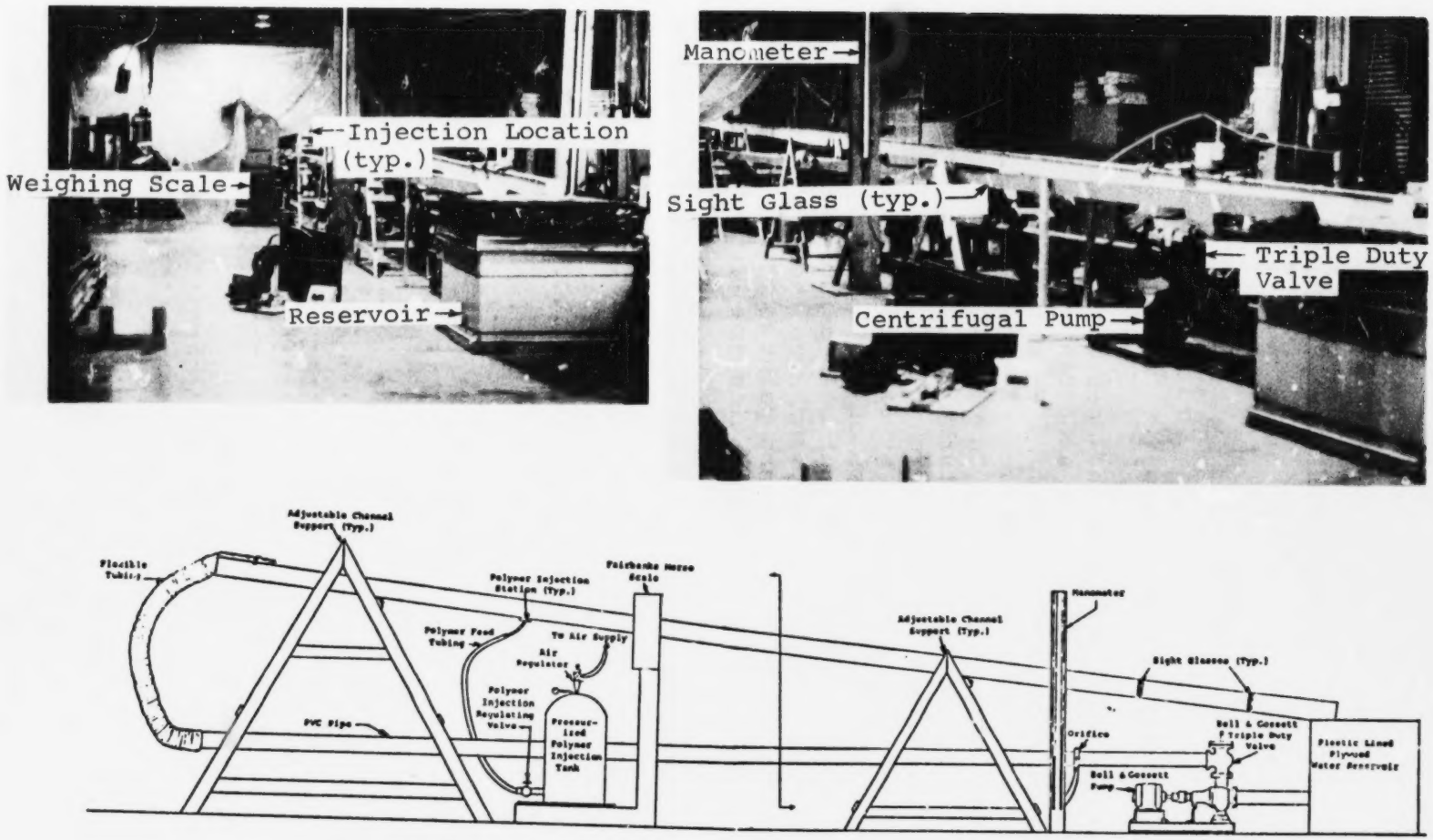

FIGURE 7. EXPERIMENTAL OPEN CHANNEL TEST SETUP

A Bell and Gossett centrifugal pump (1200 gpm capacity) was used to circulate the water, and flow rates were regulated with a Bell and Gossett triple duty valve. The water was pumped from a 300-gallon open reservoir (constructed of plywood and lined with two 4-mil plastic sheets), through a 10-foot, 6-inch diameter Simplex metering tube with orifice, into 50 feet of 6-inch diameter PVC plastic pipe, through 10 feet of flexible hose, into one of the channel configurations. The flow then returned to the reservoir via the channels, to complete the closed loop. Flow rates within the open channel system were measured using an orifice plate and two manometer tubes, located at the Simplex metering tube (Fig. 8a.). The manometer tubes were connected to two pressure taps, one on each side of the orifice plate, and sensed a pressure differential. Other instrumentation used included a pitot-static tube and four sight glasses per channel. The pitot-static tube was used to determine local velocities (for the theoretical analyses), flow depths, and flow velocity increase. The tube was adapted to a mechanical positioner (Fig. 8b.), so that it could function at any point in the flow volume. The sight glasses were constructed of plexiglass and were etched at 1/8-inch increments, enabling flow depths to be measured. The glasses were located at the downstream end of the channel test sections and were spaced at 5-foot intervals.

Preparation of Polymer Solutions

Since larger quantities of polymer solution were required for the open channel testing, solutions were mixed in a 54-gallon drum fitted with a two-bladed agitator (Fig. 9a). The agitator was driven with a 1/15 hp, 66 rpm Dayton gear motor. Three polymer solutions were prepared using this apparatus: Polyox Coagulant; Polyox WSR-301; and Separan AP-30. The polymers were mixed in 42-gallon batches and at 1% concentrations.

The preparation of Polyox solutions was accomplished by first pre-dispersing the powder in anhydrous isopropanol. The slurry was then added to water which was being stirred at 66 rpm. The stirring was continued until a uniform solution was obtained. It was found that the simplest way

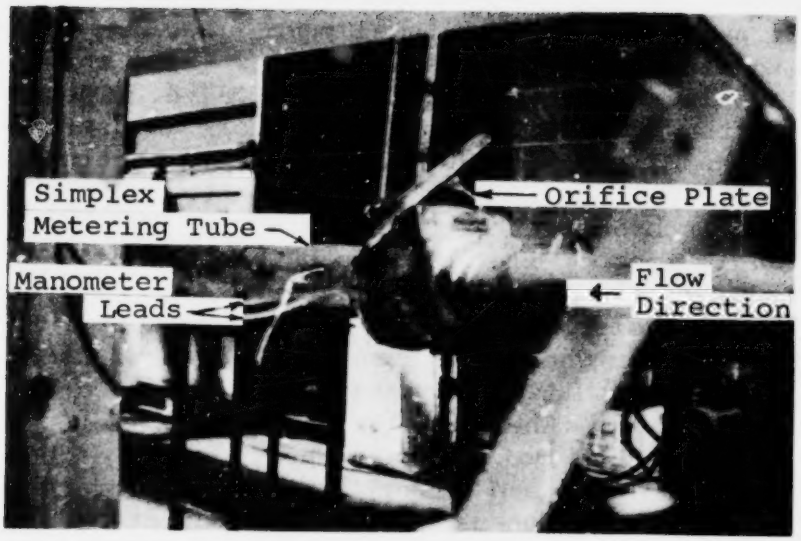

FIGURE 8a. SIMPLEX METERING TUBE WITH ORIFICE

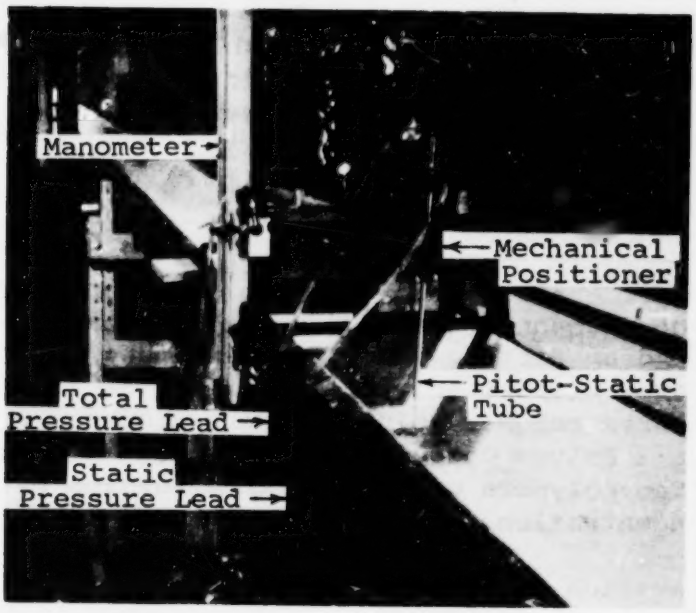

FIGURE 8b. PITOT-STATIC TUBE TEST ASSEMBLY

to prepare the solutions was to mix them in four stages; one-quarter of the total quantity was mixed in each stage. When this was done, a better dispersion of polymer was achieved, and the tendency to form polymer "clumps" was minimized. The Separan AP-30 solutions were mixed using a technique similar to the one used for the small-scale tests. A weighed polymer sample was sifted into water which was being stirred in the 54-gallon drum. When all of the powder was dissolved, the stirring was stopped. As was done above, the solution was prepared in four stages.

Polymer Injection Procedures

Two basic components of polymer injection systems were investigated prior to selecting the system (Fig. 9b) used for the open channel tests. The first component investigated was the forcing device. Two were considered: a mechanical pump, and a compressed air pump. Since compressed air at the pressures needed was readily available and the cost of a mechanical metering pump which would satisfy the requirements was too high, the compressed air device was used for the open channel tests. As shown, this device consisted of a 42-gallon pressure tank and a 120 psig compressed air supply. The air pressure was varied and maintained by using a pressure regulator attached to the tank. In operation, different polymer solutions flow rates were obtained by changing the pressure settings. To measure the weight flow of polymer solutions, a Fairbanks Morris scale and a stop watch were used. The injection was started and/or stopped with a gate valve connected to the tank and transfer tubing.

The second component investigated was the device used for injection of the polymer into the open channel once the polymer was forced out of the pressure tank. Four such devices were evaluated, the first two being selected for the open channel tests (see page 39). Each was rated according to its ability to disperse the polymer throughout the flow volume. A red dye was mixed with the polymer solution, and the degree of polymer dispersion in the flow was visually observed.

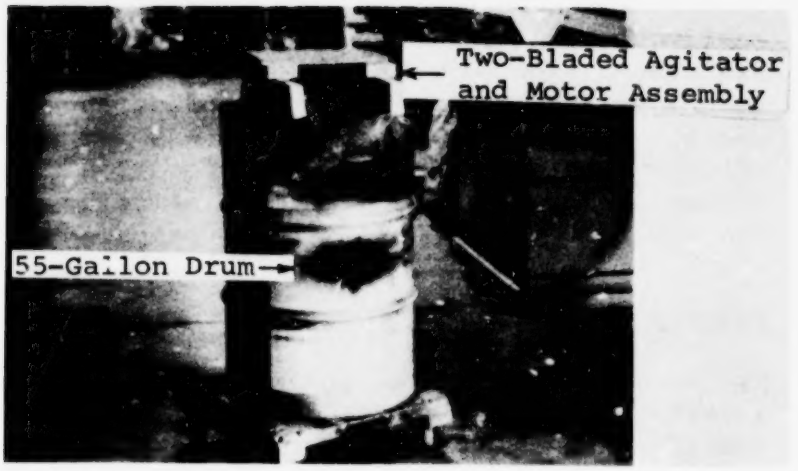

FIGURE 9a. POLYMER MIXING DEVICE
(OPEN CHANNEL TESTS)

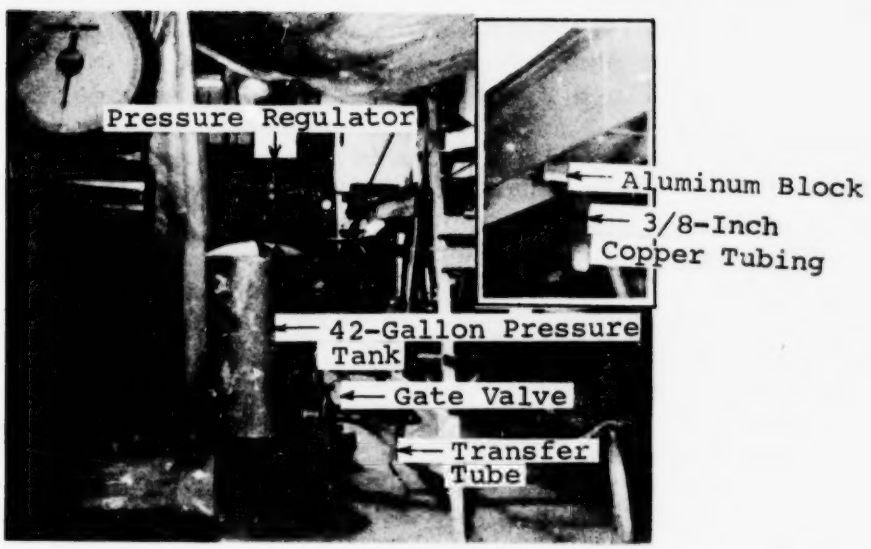

FIGURE 9b. POLYMER INJECTION SYSTEM
(OPEN CHANNEL TESTS)

The first injection device investigated consisted of an aluminum block drilled through at a 45° angle, and fitted with a section of 3/8-inch copper tubing. The block was attached to the underside of the channel with epoxy glue. A 20-foot section of 3/8-inch Tygon tubing connected the pressure tank to the injection device.

The second device was similar in construction to the first; however, instead of injecting at a point, injection was accomplished over an area. This was done by taping a strip of screen (4 inches by 6 inches) across the bottom of the channel, covering the outlet of the injection device.

The third device was a plastic injection manifold. It was constructed of plexiglass and had a 1-inch diameter inlet which was connected to the pressure tank with a 10-foot section of 1¼-inch flexible tubing. The polymer was injected into the flow through sixteen 5/16-inch holes. The holes were evenly spaced across the lower sides and bottom of the channel. This device was designed to fit into the rectangular channel only.

The fourth device was the simplest. A 20-foot section of 3/8-inch Tygon tubing was used. One end of the tubing was connected to the pressure tank and the other end was placed inside and along the bottom centerline of the channel. The polymer was introduced in the direction of the water flow. To minimize the flow obstruction, only 10 inches of the tubing were placed inside the channel.

Experimental Test Procedure

Three polymers, selected from the 3/4-inch pipeline calibration tests, were used for testing in the open channel test facility. The first set of tests was conducted in the smooth-walled channel. Each polymer was tested in two channel configurations, at three slopes (1%, 2%, and 4%) and at two Reynolds numbers (5×10^4 and 8.5×10^4).

The procedure to determine polymer effectiveness commenced by setting an initial Reynolds number. This was accomplished by adjusting the flow rate until a combination of the flow

velocity and the hydraulic radius produced one of the above Reynolds numbers. Once this flow rate was obtained, the following data were recorded:

Date
Channel slope
Orifice readings
Pitot-static readings
Water level - sight glasses
Initial weight of polymer in pressure tank
Polymer injection pressure.

Polymer was then injected into the flow at a point 49 feet upstream of the reservoir. The injection point was located along the bottom centerline of the channel.

As a result of polymer injection, a decrease in the water level or static head occurred. Thus, the system was given sufficient time to reach an equilibrium state, and a measurement of the new water level was then made, using both the sight glasses and pitot-static tube. After recording this measurement, the flow rate was increased until the level returned to its original value. The polymer injection was subsequently stopped, and the data listed below were recorded:

Orifice readings
Time of polymer injection
Final weight of polymer in pressure tank.

Using a manufacturer-supplied orifice plate calibration curve and Equation (1) of Appendix 2, the percent flow augmentation was calculated.

The next step was to reset the flow rate in the channel to the same initial rate by closing the triple duty valve. Once this was accomplished, the water levels were checked to make sure that they returned to their original levels. If they did not, it was necessary to change the water in the system to prevent a polymer concentration buildup.

After the initial conditions were re-established, the pressure tank was set at a different pressure, and polymer was injected into the flow. The same data as before were

recorded. The procedure was repeated at least four times for each polymer solution, and each time a different polymer injection rate was used. The percent flow augmentation was expressed in terms of the bulk polymer concentration in the flow. The concentrations were calculated using Equation (3) of Appendix 2.

Tests to determine the effect of channel surface roughness on flow augmentation were also performed, using the most effective polymer found for the smooth surface tests. The same two channel configurations (with a different degree of wall roughness) were used, as well as the same channel slopes and initial flow rates. Experimental procedures were similar to the preceding ones, and the results were similarly presented.

Three injection point locations were tested to determine the effect of the point of injection with respect to flow augmentation. These tests were performed in the smooth-wall trapezoidal channel at a 2% slope, using Polyox Coagulant. The first two injection points were located in the channel, 49 feet and 56 feet upstream of the reservoir. The third point was located in the 6-inch pipeline, 16 feet downstream of the pump. The methods of injection were the same as those used in the polymer performance tests; however, for the third point of injection, the polymer was introduced through the pipeline into the flow.

Each injection point was evaluated in terms of the maximum flow augmentation produced at a constant static head. The polymer concentration in the flow was varied by changing the injection rate, and the results were presented graphically. The experimental procedure followed the same steps as the procedure outlined for the smooth- and rough-wall open channel tests.

OPEN CHANNEL POLYMER PERFORMANCE RESULTS

Polymer Performance in Smooth Surface Channels

Polymer performance or effectiveness in smooth-wall open channels has been illustrated by using a number of graphical methods. The first of these methods uses curves

representing the experimentally determined flow augmentation versus the injected polymer concentration. These curves are shown on Figures 10, 11, and 12, and are plotted for two Reynolds numbers, two channel configurations, and three channel slopes.

Figure 10 shows the effectiveness of Polyox Coagulant. It is seen that, in general, this polymer is most effective in rectangular smooth-wall channels, and at lower Reynolds numbers. The same results have been obtained for Polyox WSR-301 and Separan AP-30, as seen in Figures 11 and 12, respectively. These plotted data also indicate that a maximum flow increase occurs at a relatively low polymer concentration (between 20 and 30 wppm) and, unlike the results found for pipeline flow, the flow augmentation does not continually increase, but rather levels off or, in some cases, begins to decrease with increasing concentration.

In order to compare these experimental results with those obtained by other investigators, a portion of Figure 11 has been expanded and is shown on Figure 13. It is seen that this curve plotted for Polyox WSR-301 in a rectangular channel flow at a Reynolds number of 5×10^4 and slope of 2% compares well with data obtained from Reference 6 for the same polymer under similar conditions in a partially filled pipeline. Note also that, as shown, the same trends appear in this reference data when comparing pipeline flow to open channel flow.

In addition to the above curves, another graphical representation has been made. Figures 14a and 14b represent the maximum percent flow augmentation obtained from Figures 10, 11, and 12 plotted against channel slopes. In these figures a general trend is indicated, in which flow augmentation decreases and then increases with slope increase. However, this polymer effectiveness dependency on channel slope is not concrete, since it is not indicated by all data points.

Visual results of polymer effectiveness are typically shown in Figure 15. As indicated, a water surface level drop was produced as the polymers were injected into the flow. The extent of this drop was directly dependent on the injected polymer concentration.

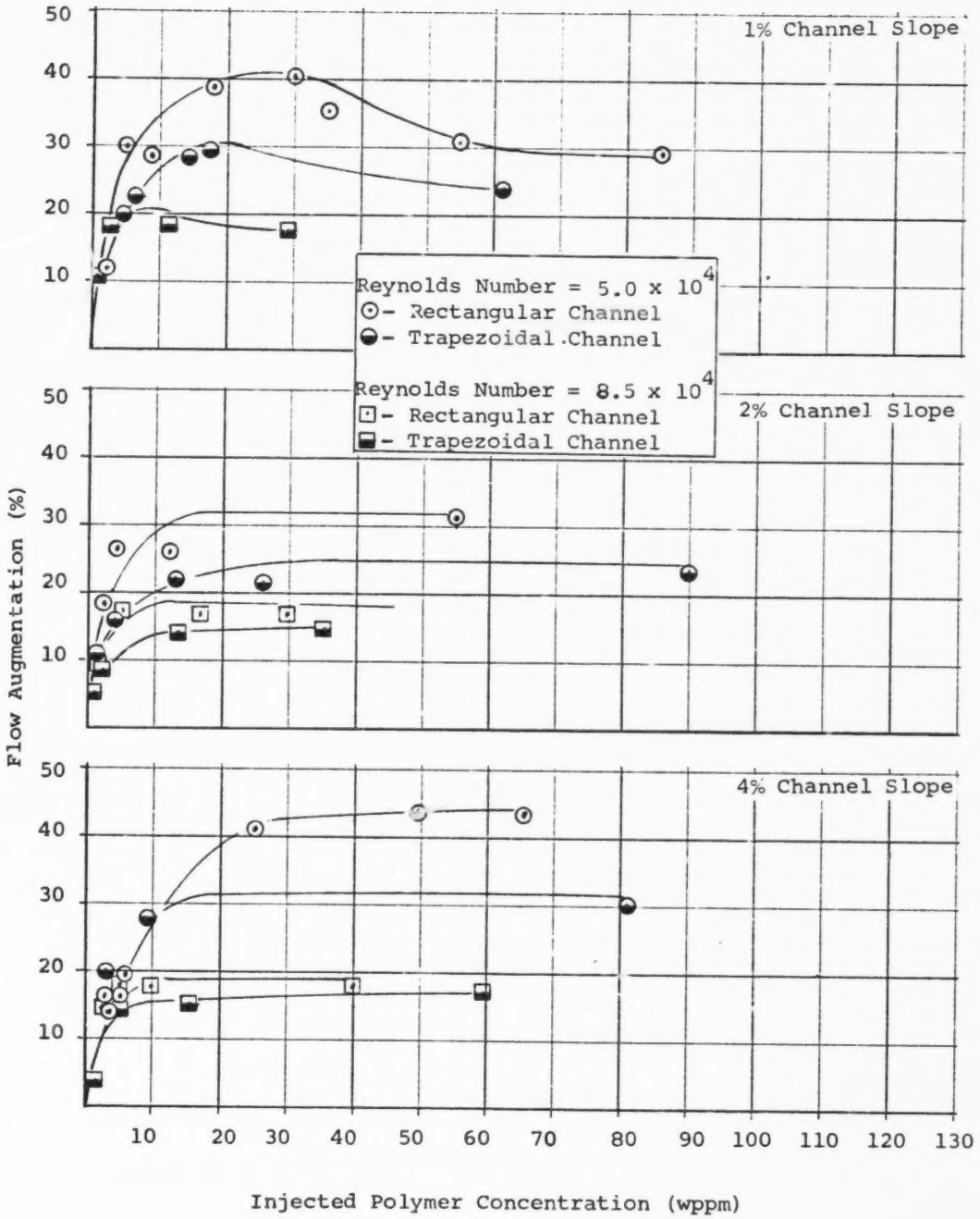

FIGURE 10. SMOOTH-WALL OPEN CHANNEL POLYMER PERFORMANCE (POLYOX COAGULANT)

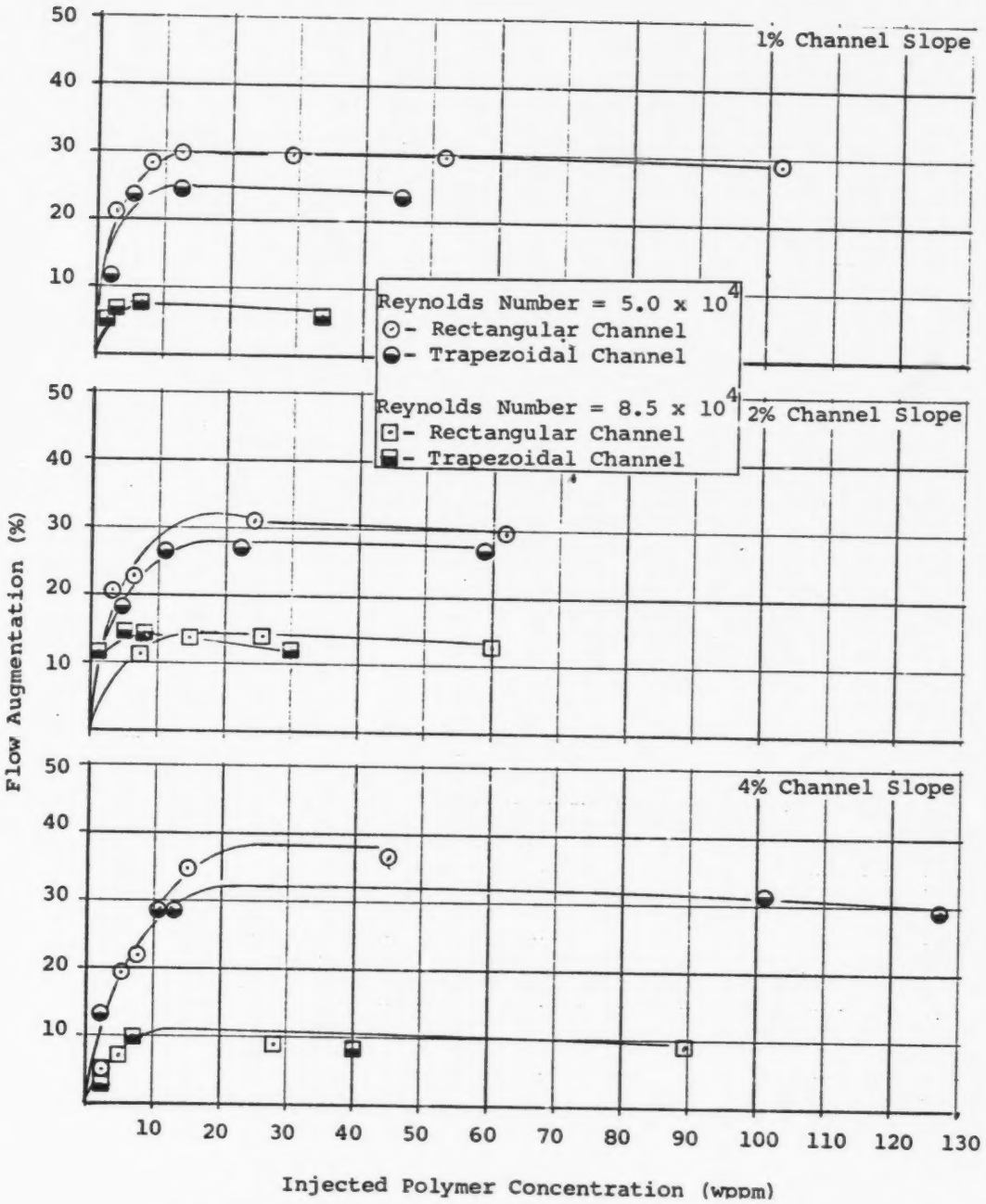

FIGURE 11. SMOOTH-WALL CHANNEL POLYMER PERFORMANCE (POLYOX WSR-301)

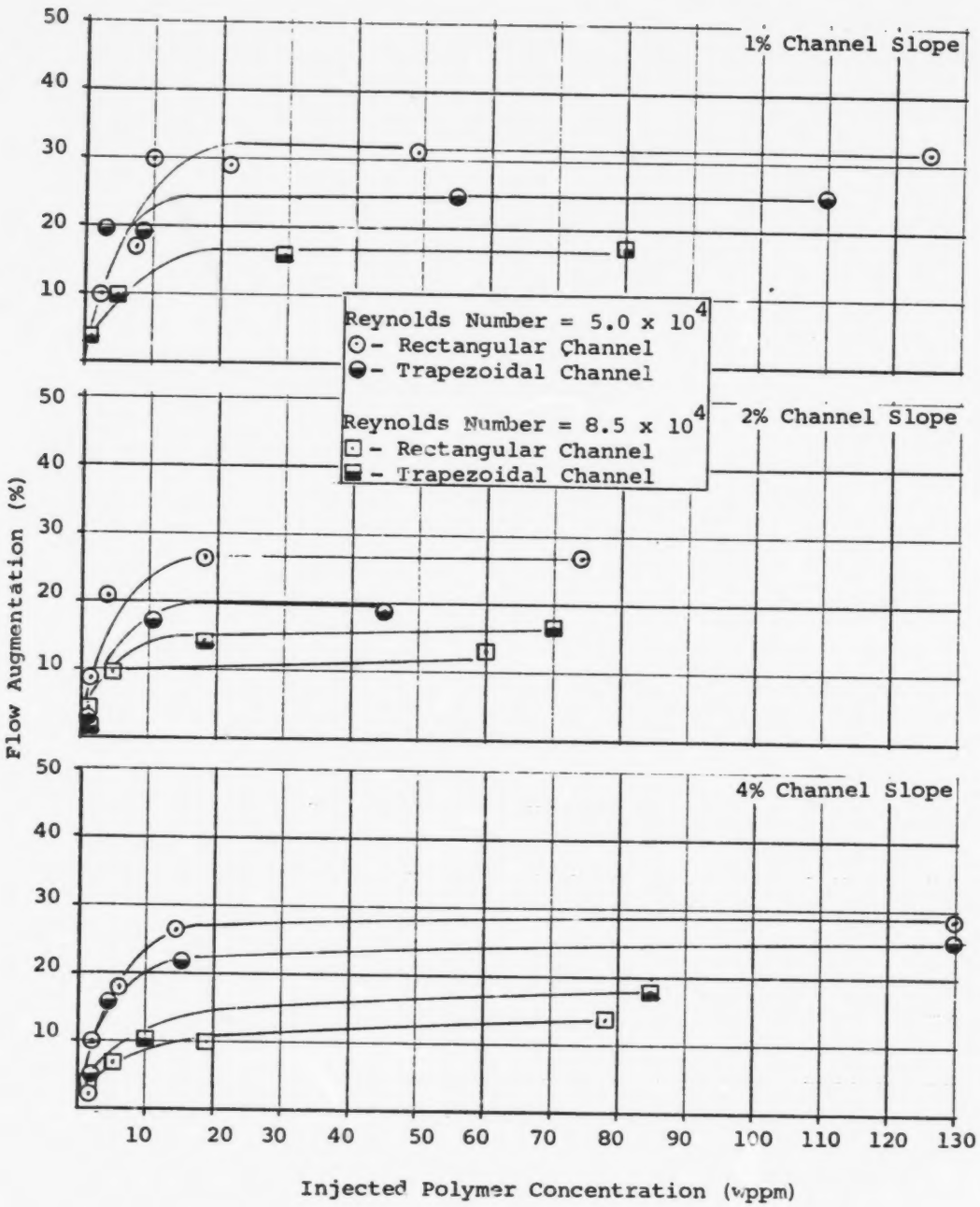

FIGURE 12. SMOOTH-WALL OPEN CHANNEL POLYMER PERFORMANCE (SEPARAN AP-30)

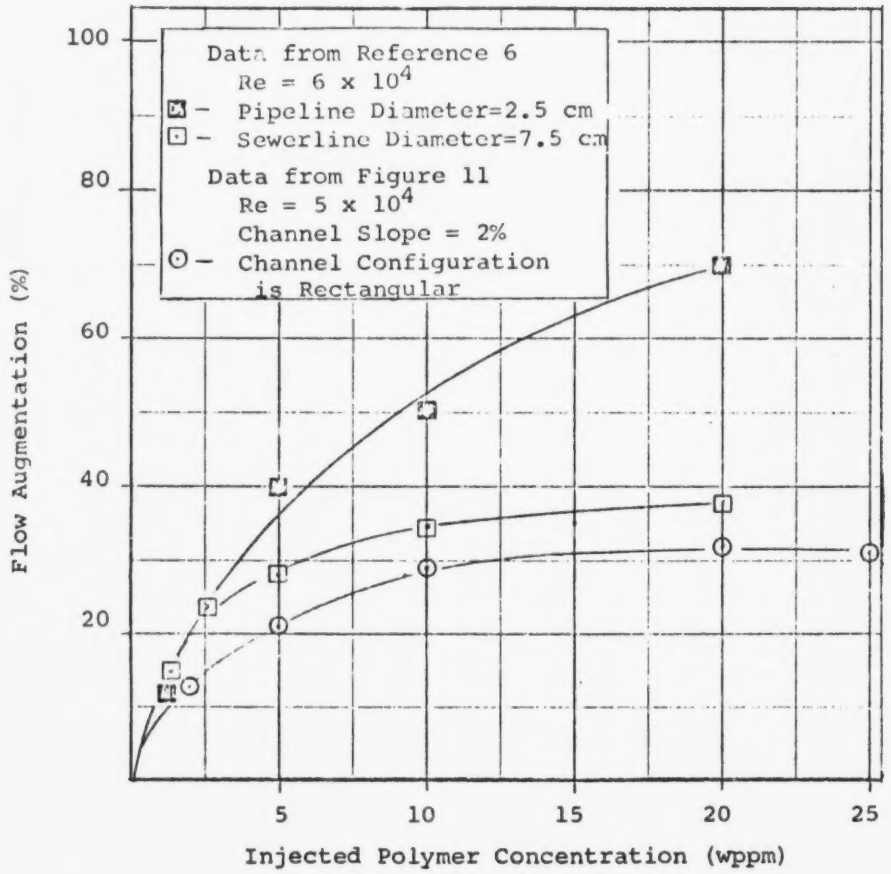

FIGURE 13. REFERENCED DATA COMPARED TO PRESENT OPEN CHANNEL DATA (POLYOX WSR-301)

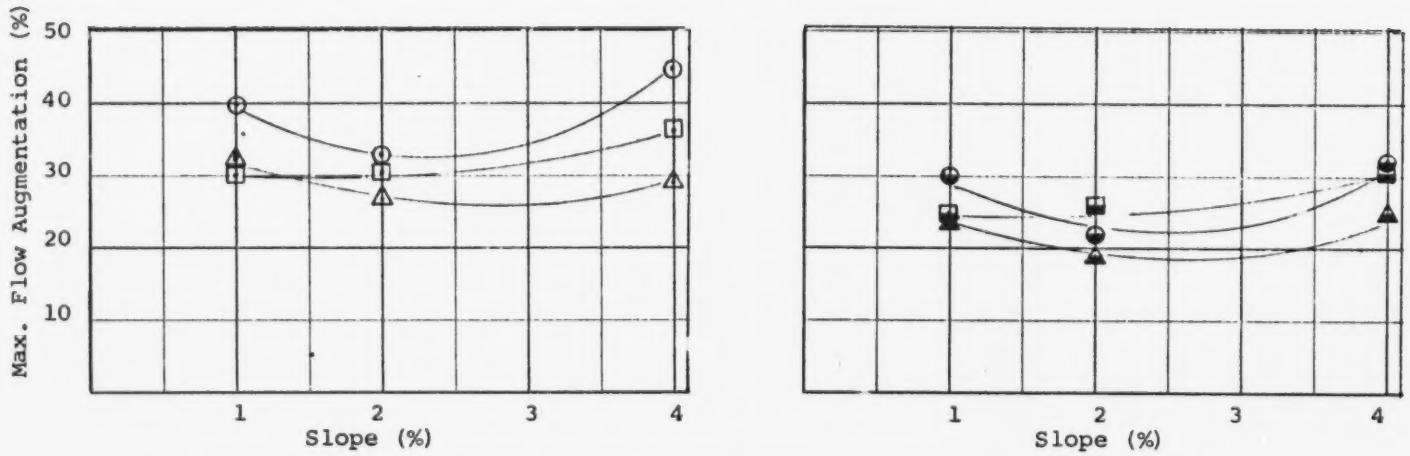

FIGURE 14a. MAXIMUM POLYMER EFFECTIVENESS (Re = 5.0×10^4)

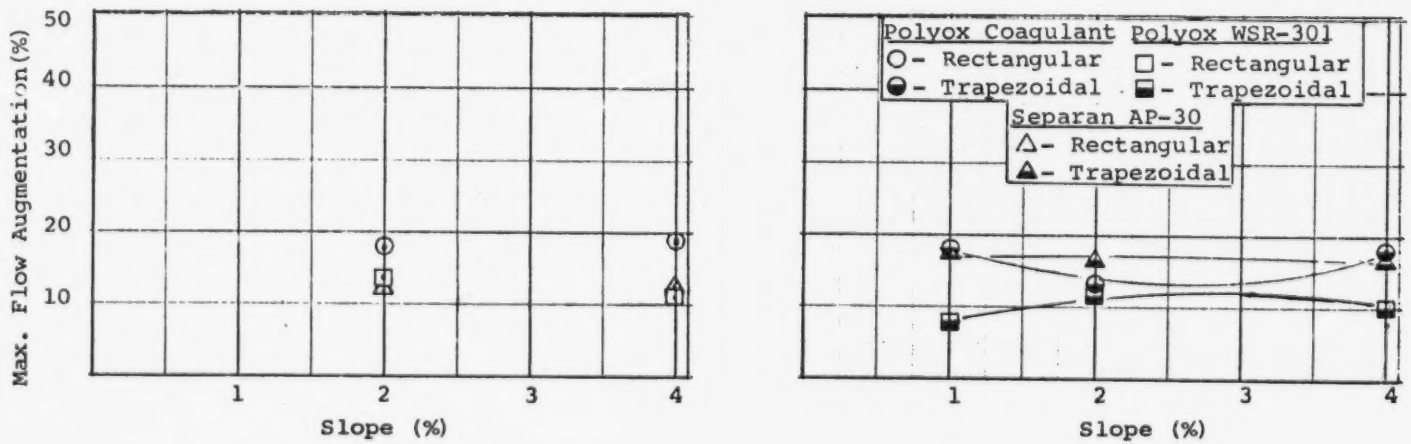

FIGURE 14b. MAXIMUM POLYMER EFFECTIVENESS (Re = 8.5×10^4)

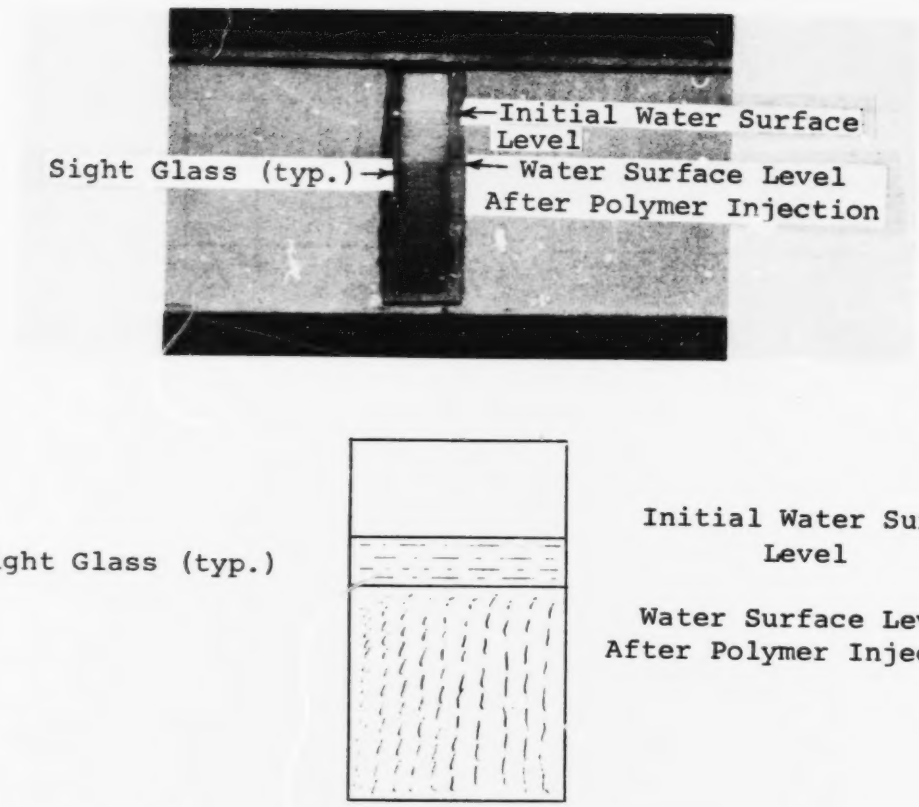
Initial Water Surface Level
Sight Glass (typ.)
Water Surface Level After Polymer Injection
Sight Glass (typ.)
Initial Water Surface Level
Water Surface Level After Polymer Injection

FIGURE 15. VISUAL RESULTS OF POLYMER PERFORMANCE (OPEN CHANNEL TESTS)

Summarizing the above results, it is found that:

1. Generally, Polyox Coagulant is the most effective polymer under all test conditions. This polymer is followed in effectiveness by Polyox WSR-301 and Separan AP-30, respectively.

2. For the same Reynolds numbers and slopes, a higher maximum flow augmentation was produced in the rectangular channel configuration.

3. The maximum effectiveness of each polymer additive occurred at relatively low concentrations (20 - 30 wppm).

4. Flow augmentation is dependent, in varying degrees, on flow Reynolds number and channel slope.

Effect of Channel Surface Roughness

Using Polyox Coagulant, the smooth-wall performance tests were repeated in rough-wall channels. Flow augmentation was obtained as a function of the additive concentration at a constant static head. The results are presented in Figure 16, and are compared to the smooth-wall data as follows:

1. The concentration at which Polyox Coagulant reached its maximum effectiveness was increased from approximately 25 wppm to approximately 50 wppm.

2. At the higher flow Reynolds numbers, greater flow augmentation was achieved in the rough-wall channels. For example, in the rectangular channel at a 2% slope, the maximum flow augmentation was increased from 19% to 32%.

3. A trend has been established indicating that polymer effectiveness represented by flow augmentation decreases as slope increases for the high Reynolds number, and essentially remains the same for the lower Reynolds number.

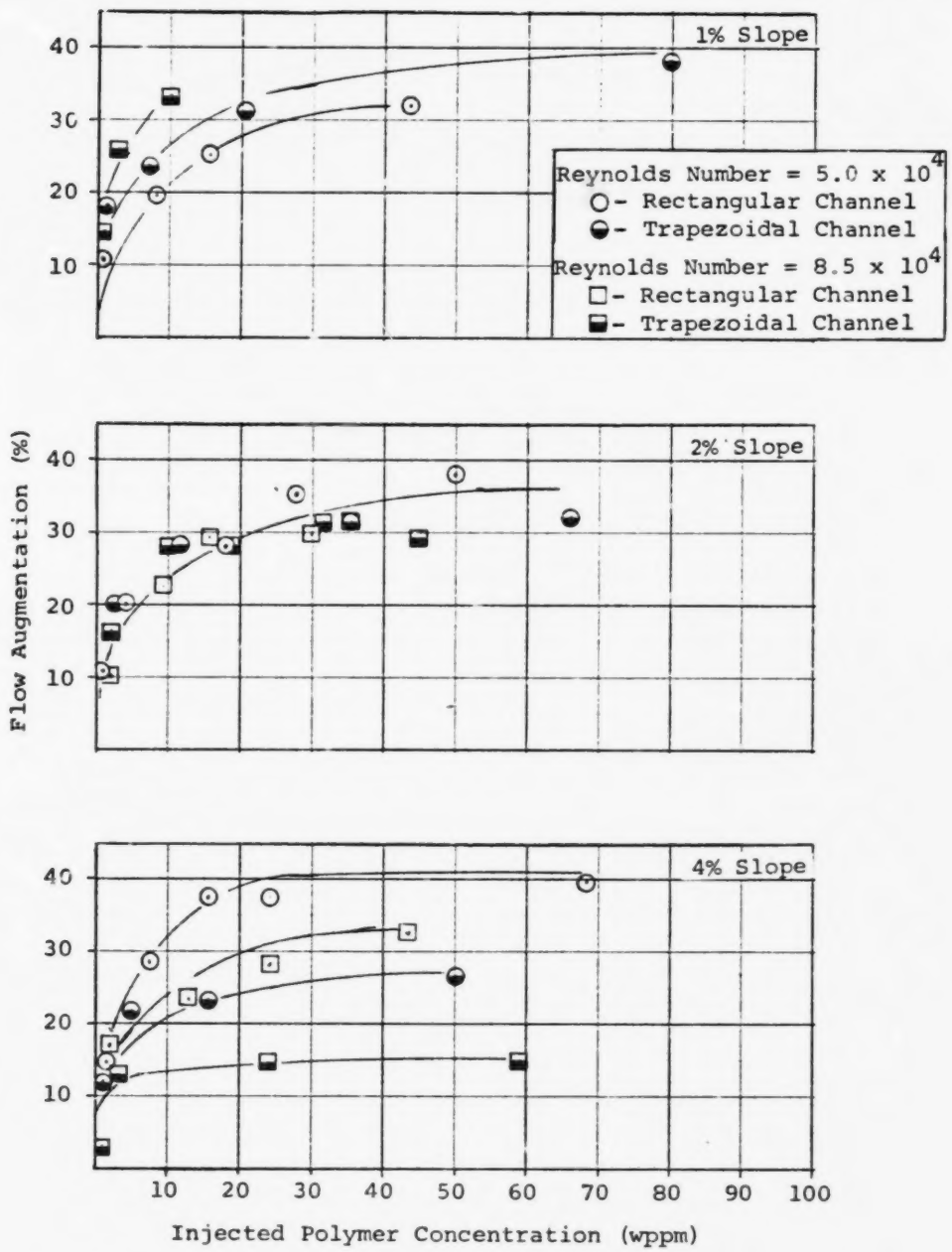

FIGURE 16. ROUGH-WALL OPEN CHANNEL POLYMER PERFORMANCE (POLYOX COAGULANT)

Injection Point Location

Polyox Coagulant was injected into the flow at three different locations. The results (Fig. 17) show that as the distance traveled by the polymer additive was decreased, the maximum obtainable flow augmentation was decreased. When injection occurred approximately 110 feet from the test section, a flow augmentation of 44% was achieved. As the distance of injection decreased to 56 feet and 49 feet, the maximum flow augmentation was decreased to 20.5%, respectively.

Polymer Injection System

The injection system previously shown in Figure 9b was found to be the most efficient for the particular test setup used. As shown, it consisted of a compressed air pump and an aluminum block fitted with a section of 3/8-inch copper tubing, and utilized both injection over an area, and injection at a point. It was found that injection over an area provided better polymer dispersion at the injection site; however, at a location 10 to 20 feet downstream, little difference was noted between the area and point injection. Both resulted in a good dispersion of polymer with minimum flow obstruction, and were found to be equally effective for both channel configurations. The remaining two injection devices were found to be unsatisfactory for the following reasons:

1. The plexiglass device obstructed the flow.

2. The 3/8-inch flexible tubing failed to produce sufficient polymer dispersion.

General Observations

Besides noting a water surface level decrease with polymer addition, other observations were made concerning polymer additives in open channel flows. These are presented below.

1. As the polymer additives were injected, the characteristic turbulence and wave motion were seen to diminish and the flow became more laminar.

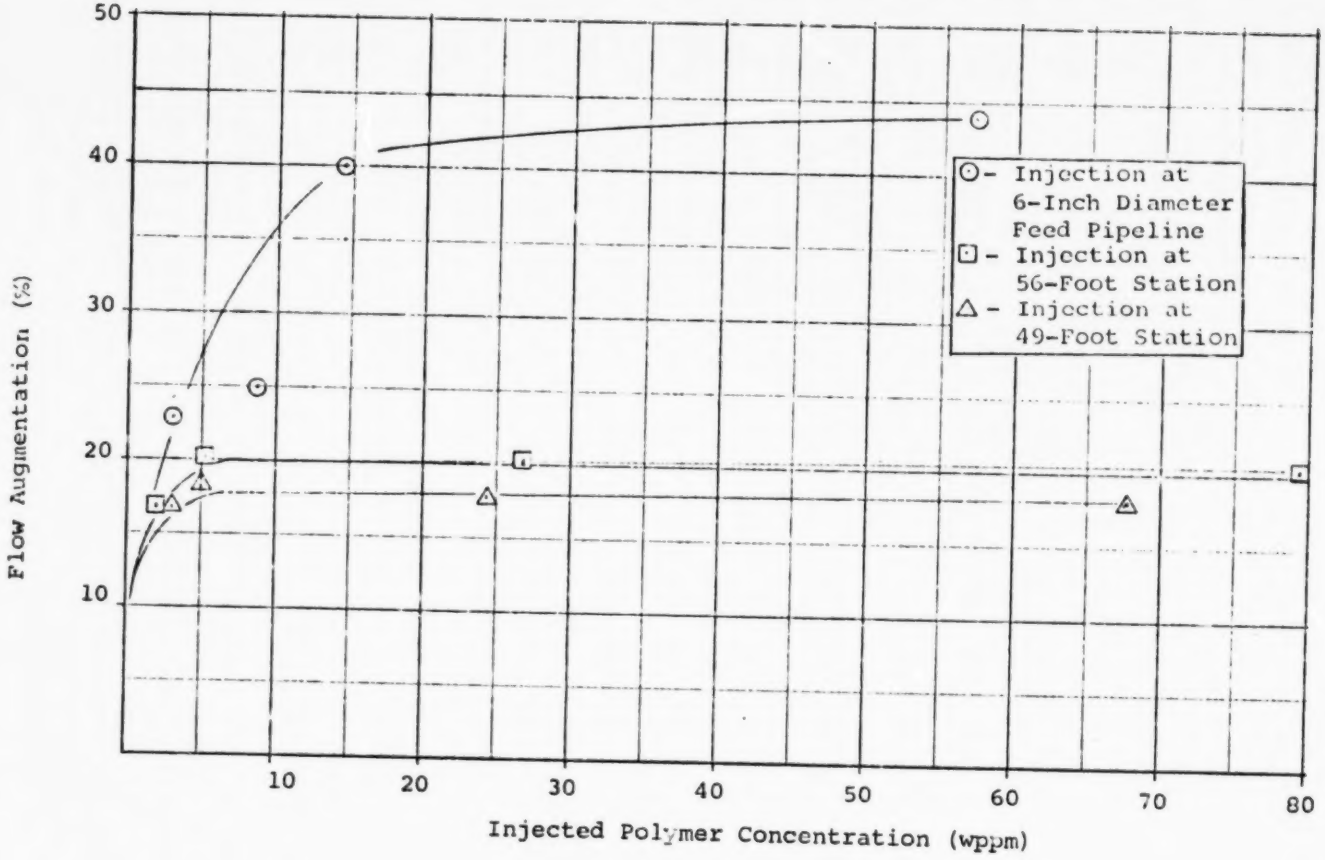

FIGURE 17. INJECTION POINT DEPENDENCE (POLYOX COAGULANT)

2. There was no polymer shear degradation noticeable within the channels tested. However, both Polyox WSR-301 and Polyox Coagulant were found to rapidly degrade when transferred through the centrifugal pump. In contrast, Separan AP-30 never totally degraded through the pump, consequently requiring complete drainage of the test system after a few test runs with this polymer.

THEORETICAL EVALUATION (VELOCITY PROFILES)

Test Procedure

Using the pitot-static tube, centerline and cross-sectional velocity profiles were initially measured for tap water flowing in each of the trapezoidal and rectangular channels. The results are shown in Figures 18 and 19, and indicate the type of flow within the channels. Centerline velocity profiles were then measured in the same two channels at two shear velocities for both water and water/polymer flows. Local velocities and corresponding depths were non-dimensionalized and graphically presented. The resulting experimental points were compared with theoretically derived curves. The theoretical curves were based on an equation derived from the Prandtl-von Karman Universal Velocity Distribution Law applied to smooth-wall open channel flow (see Ref. 7). This equation is presented in Appendix 2 as Equation (4).

Results

Comparing the theoretical and experimental results for tap water (Fig. 20), it is seen that good agreement exists. This, consequently, establishes the validity of Equation (4) with respect to the flow in the two channel configurations. Polyox Coagulant injection into the flow results in new non-dimensionalized profiles as shown in Figure 20.

When compared with the curves for undosed tap water, an upward shift is noted in each case. This shift, accounting for the velocity increase, is represented by a constant, " ΔB", which when inserted into the Universal Velocity Distribution Law, yields Equation (5) in Appendix 2. In

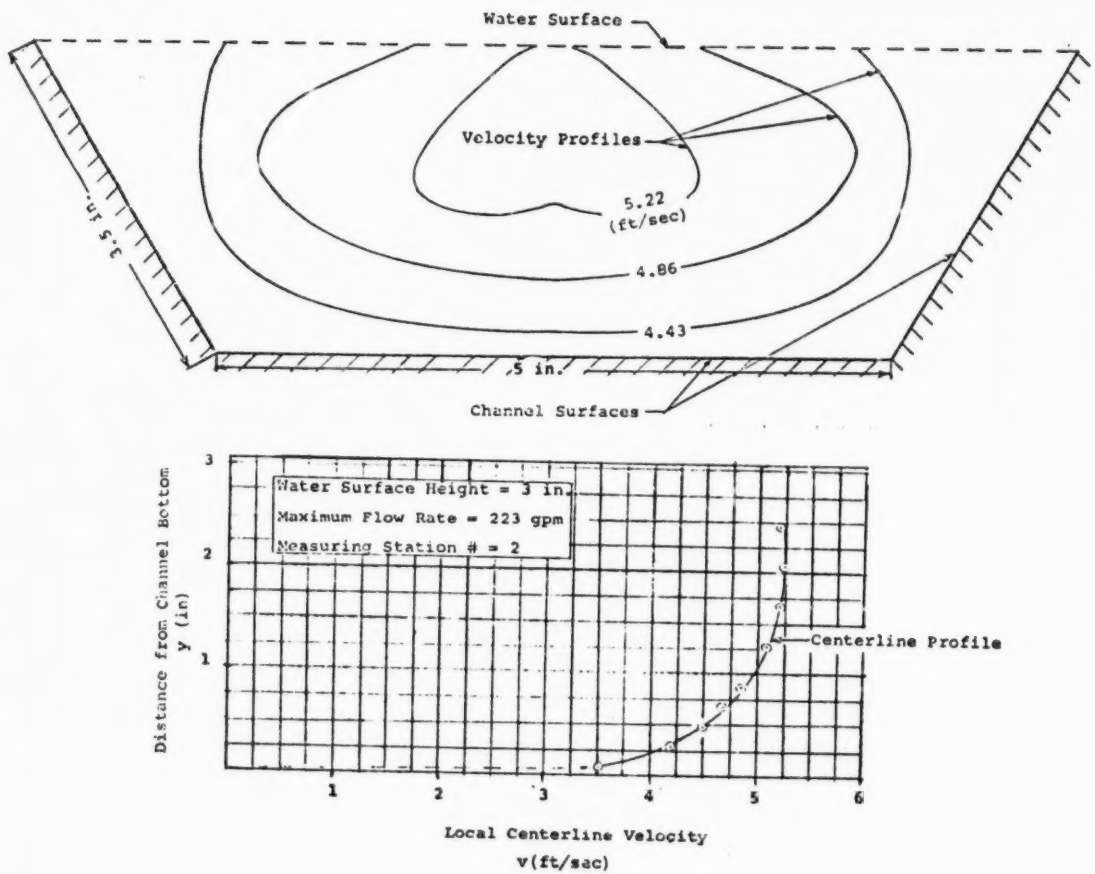

FIGURE 18. TYPICAL VELOCITY PROFILES FOR TRAPEZOIDAL OPEN CHANNEL

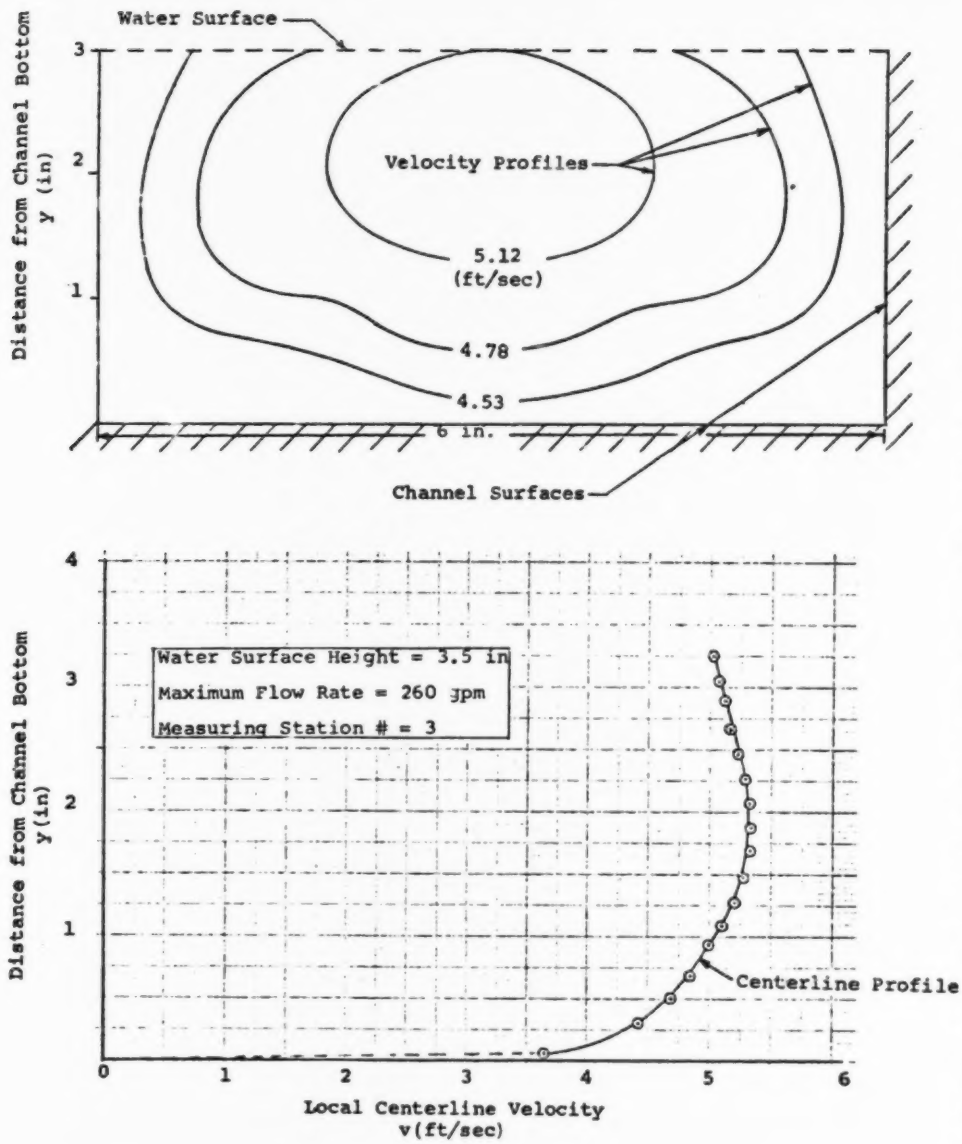

FIGURE 19. TYPICAL VELOCITY PROFILES FOR RECTANGULAR CHANNEL

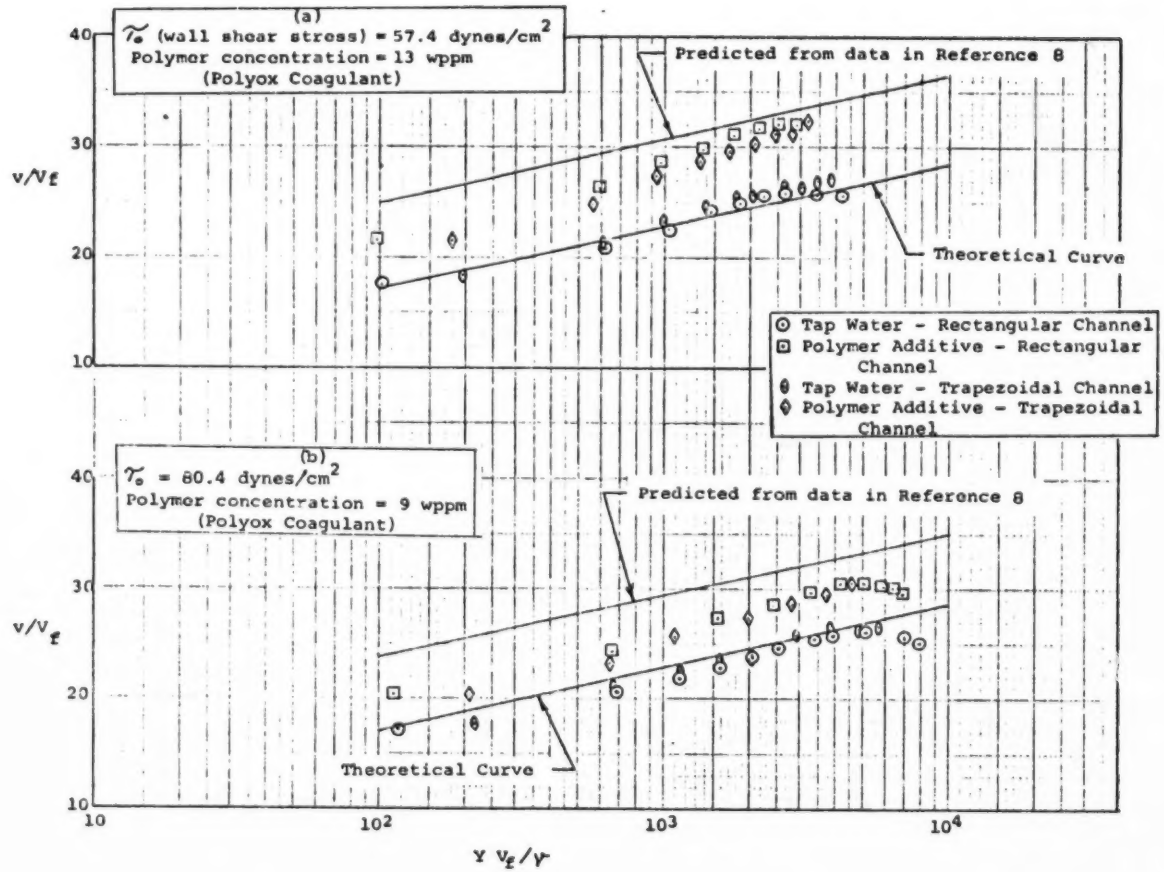

FIGURE 20. THEORETICAL VELOCITY PROFILES COMPARED TO THOSE EXPERIMENTALLY DETERMINED IN AN OPEN CHANNEL AND PIPELINE

theory, this constant is a function of the polymer additive properties and the wall shear stress. The same phenomenon is encountered in pipeline flow and flow over flat plates. The constant, "ΔB", has been evaluated for pipeline flow by several investigators, and is plotted in terms of the wall shear stress of Fabula (Ref. 8). Thus, for purposes of comparison, the "ΔB" values obtained for pipeline flow at given wall shear stresses and polymer concentrations were used in Equation (5) and a predicted curve is also plotted in Figure 20.

The experimental points found for the open channels are seen to lie below the predicted curve, indicating that the local velocity increase in open channel flow is not as great as the increase experienced in pipeline and flat plate flow.

SECTION V

FLUME AND SPILLWAY TESTS

EXPERIMENTAL TEST ARRANGEMENT AND PROCEDURES

Arrangement

A series of tests was conducted in the open channel facility to determine the effects of a polymer additive on the following four types of flow measurement devices (Fig. 21):

Leopold-Lagco flume
Parshall flume
Sharp-Crested weir
V-notch weir.

The Parshall flume and the sharp-crested weir were adapted to the smooth-wall rectangular channel and tested at a 1% slope, while the V-notch weir and the Leopold-Lagco flume were tested in the smooth-wall trapezoidal channel at a slope of 2%. The additive used for this testing was Polyox Coagulant.

Procedures

The tests were conducted using the following experimental procedure. The first step was to establish an experimental calibration curve using tap water for each of above devices. The curve was obtained by measuring a static head with a pointer gauge at a specified point in the flow (usually at the inlet to the device) and recording it along with the corresponding flow rate. Since the orifice plate was only accurate for flows greater than 150 gpm, lower flow rates were determined using a stop watch, a 5-gallon bucket, and a scale. The time and weight of water required to fill the bucket were recorded. Once a sufficient number of data points were obtained, a curve was plotted expressing the head as a function of the flow rate.

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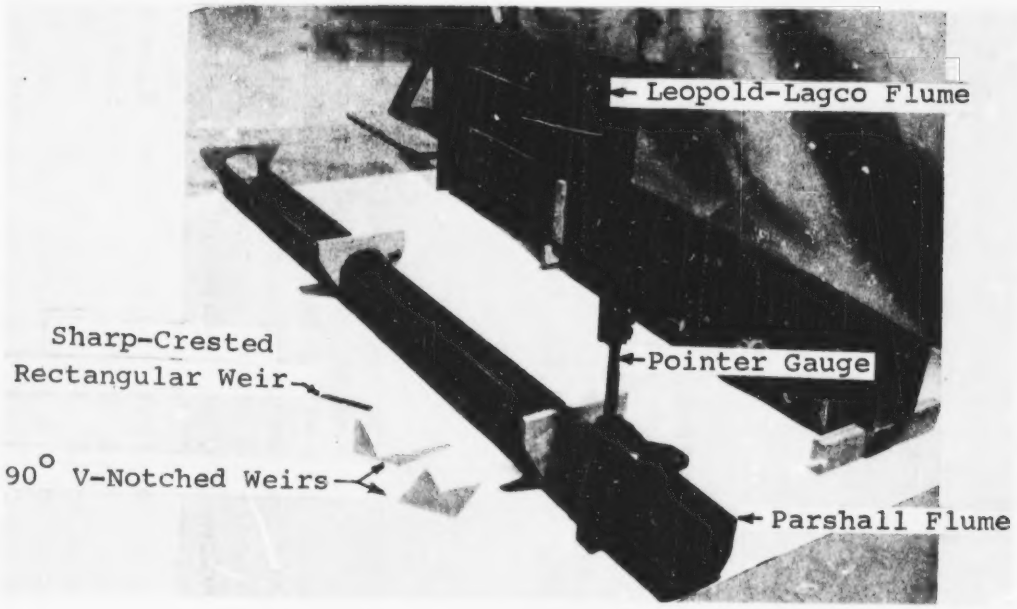

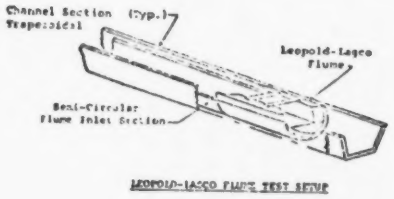

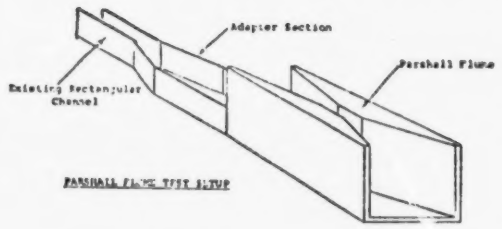

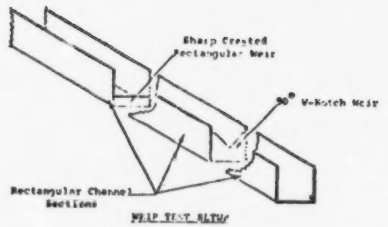

FIGURE 21. FLUMES AND SIDE CHANNEL SPILLWAYS

The next step was to introduce polymer into the flow. The polymer was injected at a rate required to yield a predetermined concentration. The same procedure as above was repeated, and a new calibration curve was developed for each device at a given polymer concentration.

TEST RESULTS

Results from the flume and spillway tests are presented in Figures 22, 23, and 24. Comparison of the undosed tap water data (experimentally determined versus manufacturer supplied or calculated) shows that for the Leopold-Lagco flume (Fig. 22), the 90° V-notch weir (Fig. 23a), and the sharp-crested weir (Fig. 23b), the experimental data lie below the manufacturer supplied or calculated data. For the Leopold-Lagco flume, the discrepancy is due to the fact that the experimental data was plotted for a 2% channel slope whereas the manufacturer's data was plotted for a 0-1% slope. In the case of the weirs, the discrepancies occurred because the calculated calibration data did not take into account the finite stream velocity immediately upstream of the weirs. As shown in Figure 23a, the experimentally determined data agree well with an adjusted calibration curve when the upstream velocity is considered.

Figures 22 and 23a show that two of the flow measurement devices -- the Leopold-Lagco flume and the sharp-crested weir -- are ineffective above a transition flow rate when polymer is added to the flow. At this flow, the inherent hydraulic jump created by the flume or spillway is dissipated, as illustrated in Figure 25. This transition flow rate occurs at approximately 29 gpm for the Leopold-Lagco flume, and above 90 gpm for the sharp-crested weir.

For the V-notch weir calibration (Fig. 23b), the hydraulic jump was maintained, but the polymer had an effect on the calibration at the higher flow rates, resulting in a subsequent deviation from the water calibration curve.

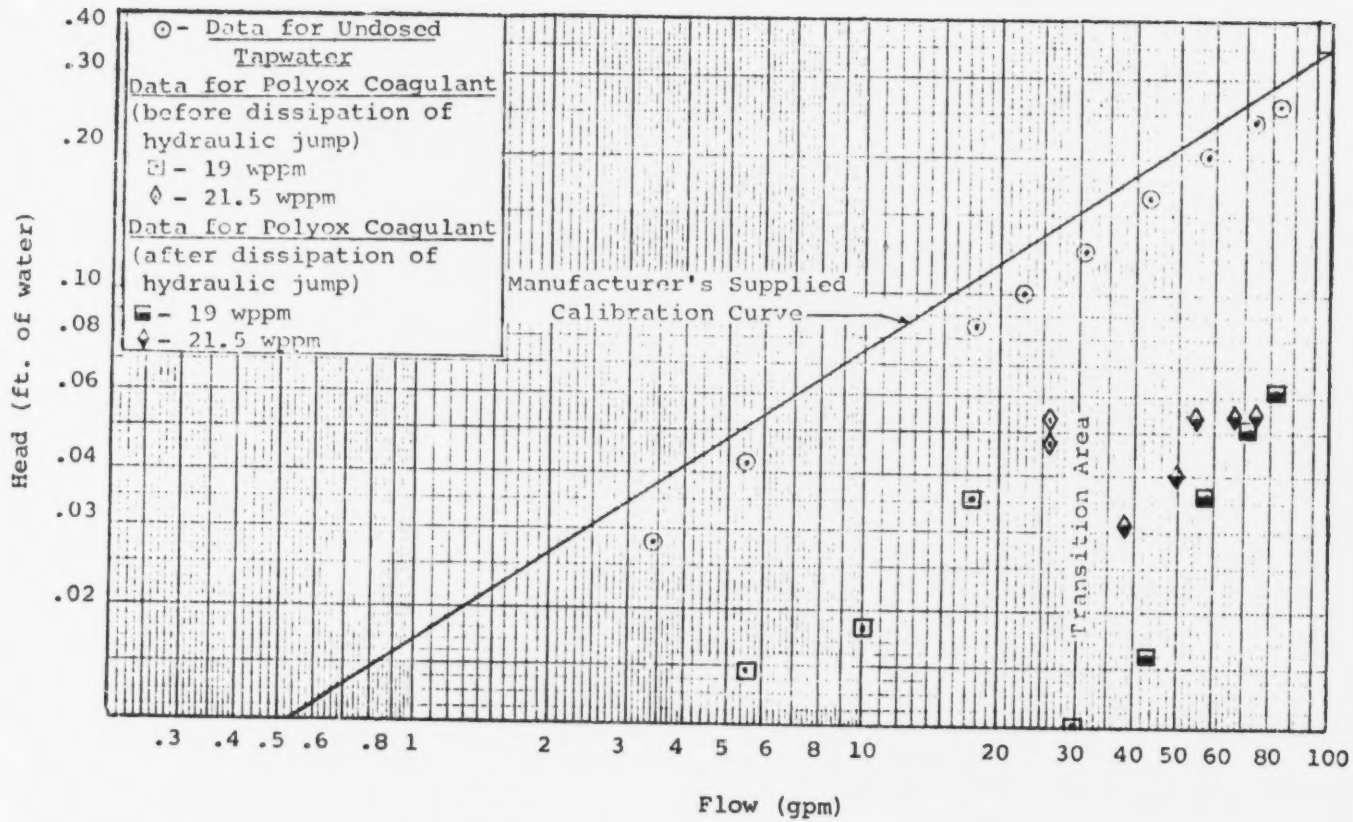

FIGURE 22. LEOPOLD-LAGCO FLUME CALIBRATION DATA (WITH/WITHOUT POLYMER)

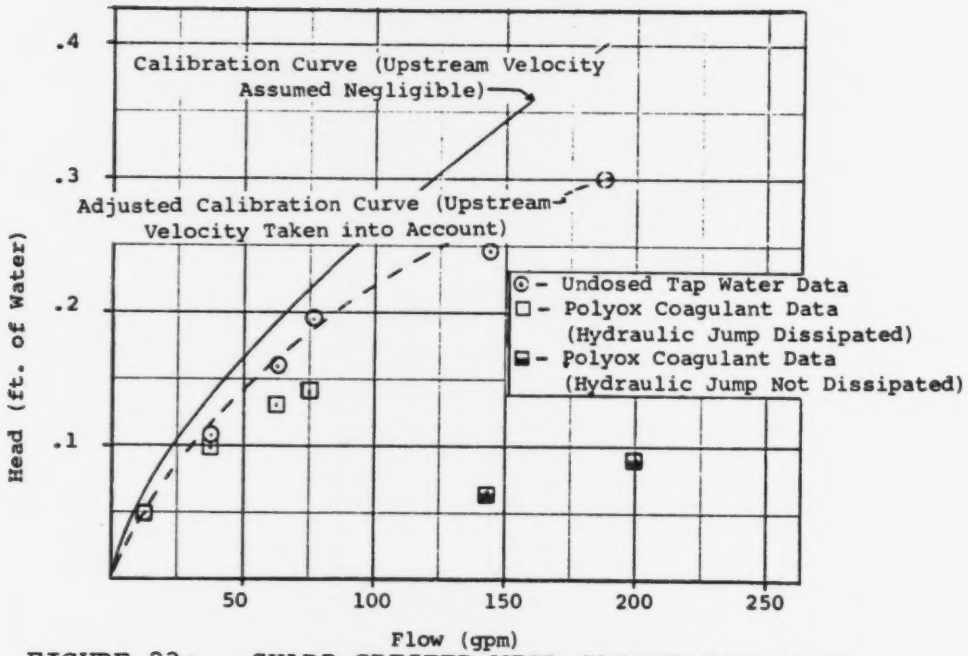

FIGURE 23a. SHARP-CRESTED WEIR CALIBRATION DATA (WITH/WITHOUT POLYMER)

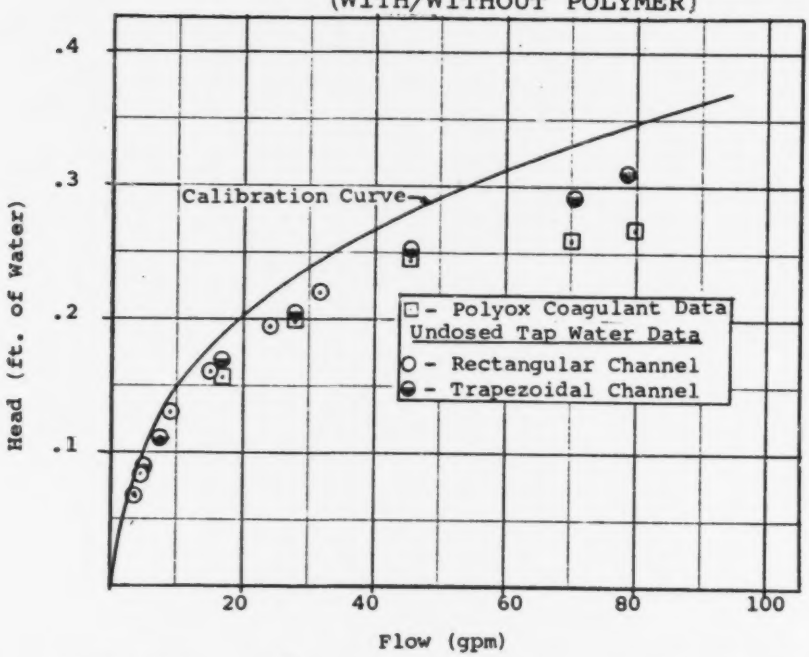

FIGURE 23b. 90° V-NOTCHED WEIR CALIBRATION DATA (WITH/WITHOUT POLYMER)

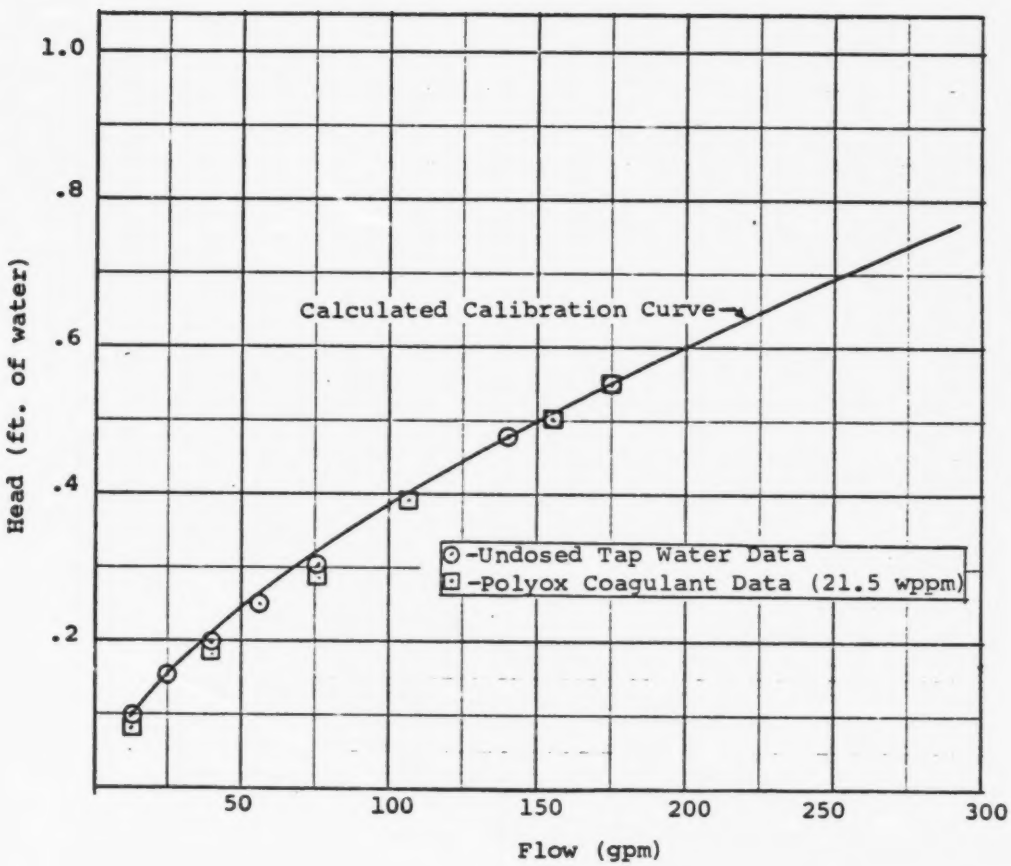

FIGURE 24. PARSHALL FLUME CALIBRATION DATA (WITH/WITHOUT POLYMER)

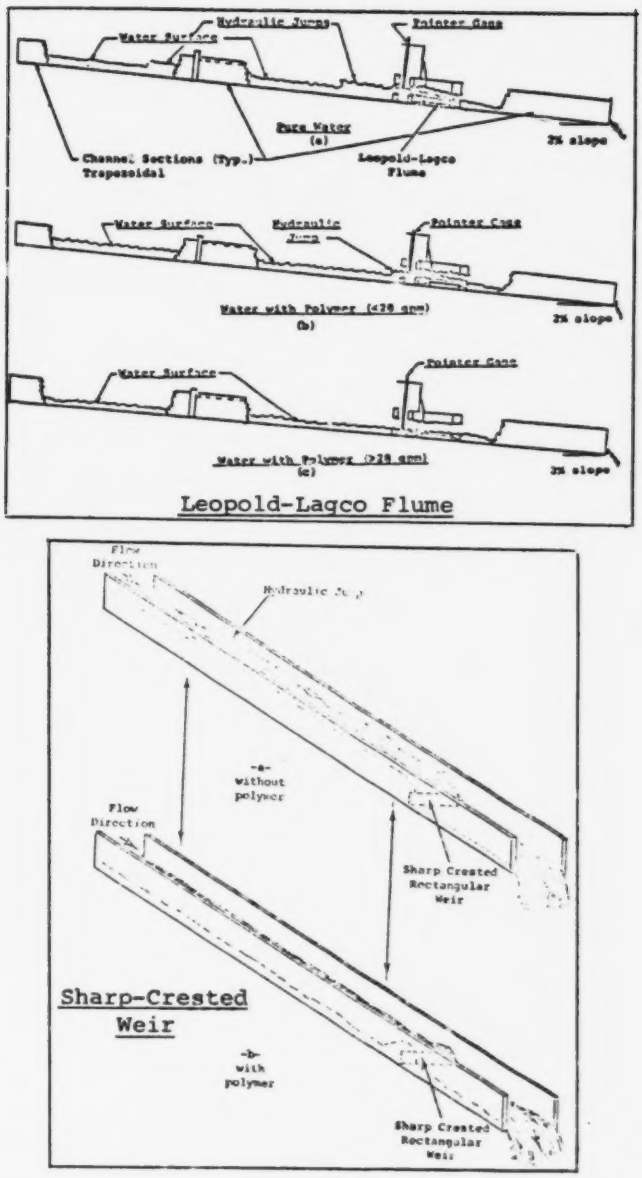

FIGURE 25. TYPICAL VISUAL EFFECTS FOUND FOR POLYMER ADDITIVES WITHIN FLUMES AND SPILLWAYS

SECTION VI

DISCUSSION

Although much pipeline information for the polymers tested is found in the literature, additional data were assimilated, using a 3/4-inch nominal I.D. pipeline to provide a means of calibrating the polymer solution concentration used for the open channel tests. Initially, the experimental data obtained in the 3/4-inch pipeline were compared to other data found in the literature, and were found to be compatible. These data were then used to establish calibration curves to test each polymer solution used for open channel testing.

In addition, from the calibration tests it was decided to eliminate Guar Gum from further testing, since relatively high concentrations of this polymer were found necessary to produce a minor flow augmentation effect in the calibration pipeline loop.

The open channel tests were performed primarily to establish what type of effect, if any, the addition of polymers would have on water flow within open channel configurations. Qualitatively, when polymer was injected into the flow, three characteristic effects on the flow were noticed. The first and most dramatic of these was that the level of the flow decreased at constant flow rate. This effect was observed for both channel configurations tested.

The second characteristic effect necessarily follows from the first, and was clearly visible. Since the flow rate before and after polymer addition was maintained at a constant value, and since the level of flow decreased upon polymer addition (decreasing the flow area), continuity of flow was satisfied only if the water velocity increased. Such a flow velocity increase was evident when the polymer was first introduced into the water flow. At this time, a mini-hydraulic jump was instantly established at the outlet of the test section. This jump indicated that the upstream flow (with polymer) was moving more quickly than the downstream flow (without polymer). This jump rapidly traversed downstream, after which the flow level decreased.

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The third characteristic effect was less noticeable. During polymer injection, a decrease in surface turbidity and wave motion was noticed. The flow seemed to approach a tranquil condition upon polymer addition. This effect was only qualitatively noted, and was not investigated thoroughly enough to establish quantitative results.

The most significant discovery during this investigation was that Polyox Coagulant, Polyox WSR-301, and Separan AP-30 exhibited a pronounced "flow augmenting" effect on the flow when injected into both rectangular and trapezoidal open channel flows. This type of effectiveness represented by friction reduction, together with flow augmentation, had been repeatedly demonstrated for completely filled pipeline flows and partially filled pipeline flows, but had never been exhibited for true open channel configurations.

Flow performance within conduits is generally expressed as percent friction reduction (at a constant flow rate), percent flow increase (at a constant energy or static head level), or a combination of both flow increase and friction reduction (mainly for gravity flows). In the case of the open channel test performed for this project, "percent flow increase" or flow augmentation was used to analyze the test data. Note also that in this project, flow augmentation percentage was experimentally determined, rather than derived from friction reduction data.

Flow increases were achieved for all test cases; however, Polyox Coagulant caused the maximum increase. Maximum flow augmentation is dependent on channel slope, but concrete relationships have not been established and this dependency is felt to be relatively minor. In the case of smooth-walled channels, it was found that a higher Reynolds number flow exhibited a lower flow increase capability. This may indicate either improper mixing of the injected polymer; that the channels used for testing were not long enough to permit adequate performance of the polymer additives; or that, at the high Reynolds number used for these tests, the specific polymers used degraded rapidly due to the shear forces. Since the rough-walled channel tests exhibited a less pronounced difference between flow augmentation for high and low Reynolds numbers, it is believed that there existed in the smooth-walled channel tests at high Reynolds number an improper polymer mixing action.

Several polymer injection systems were considered for use with this specific open channel system. It should be noted that all of the systems investigated have merit, depending upon the channel system in question. For larger scale systems, the one used for these tests is not necessarily the most adequate.

An injection point location investigation was also conducted. It was found that injection of polymer at two different locations along the open channel did not appreciably affect the flow increase results. However, injecting the polymer into the 6-inch pipeline approximately 50 feet from the entrance of the open channels did permit a greater flow increase capability. This may be due to a more thorough mixture of the polymer within the pipeline flow before it is introduced into the open channel.

Theoretically, using the Prandtl-von Karman Universal Velocity Distribution Law and experimental data obtained using a pitot-static tube within the open channels, it has been found that a flow increase shift is noted but is less than that found for pipeline and flat plate flow at the same wall shear stress. This is to be expected since, in general, the polymer effectiveness within open channels is less than that for pipeline flow.

The flume and side channel data predict that if the inherent hydraulic jump associated with these devices is dissipated by the injection of polymer, the devices should not be used for measuring the open channel flow. However, they may be calibrated for polymer flows if the hydraulic jump remains. Of all the devices tested, the Parshall flume appeared to be the most accurate.

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GLOSSARY

Force-Fed System - A flow system using mechanical means (i.e., a pump) to move the flow through the system.

Gravity-Fed System - A flow system using the force of gravity to move the flow through the system.

Hydraulic Jump - A fluid flow phenomena indicated by a sudden rise in the elevation of the liquid surface when a rapidly flowing liquid stream in an open channel suddenly changes to a slowly flowing liquid stream with a larger cross-sectional area.

Injected Polymer Concentration - The concentration of polymer expressed in weight parts per million (wppm) within the flow system being investigated.

Percent Solution - The term used to specify the amount of polymer by weight in a polymer/water or polymer/water/solvent solution used for injection into the flow system being investigated.

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APPENDIX 1

FLUID FRICTION REDUCING POLYMERS

LITERATURE SURVEY

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APPENDIX 2

FORMULAS USED FOR DATA ANALYSIS

THREE-QUARTER-INCH PIPELINE CALIBRATION TESTS

Percent flow augmentation was calculated using the following formulas:

$$\%(FA) = \frac{Q_2 - Q_1}{Q_2} \times 100\% \qquad (1)$$

where: Q_1 = initial flow rate without polymer

Q_2 = final flow rate with polymer

Polymer concentration was found by using:

$$\bar{C}_p = \frac{\rho q_1}{\bar{m}_t} \times C_p \qquad (2)$$

where: $\bar{C}_p$ = average bulk polymer injected concentration

ρ = mass density of polymer solution

q_i = volumetric rate of injection

$\bar{m}_t$ = total mass flow rate in pipeline

C_p = initial concentration of the polymer solution

OPEN CHANNEL TESTS

Polymer concentration was found by using:

$$\bar{C}_p = \frac{\dot{m}_i}{\dot{m}_t} \times C_p \qquad (3)$$

where: $\bar{C}_p$ = average bulk polymer injected concentration

$\dot{m}_i$ = injection mass flow rate

$\dot{m}_t$ = mass flow rate of water in the channel

C_p = initial solution concentration

THEORETICAL ANALYSIS (VELOCITY PROFILES)

The basic Prandtl-von Karman Universal Velocity Distribution Law can be expressed for open channel flow as follows:

$$\frac{v}{V_f} = 5.75 \log \frac{(9_y V_f)}{\nu} \qquad (4)$$

where: v = local velocity

y = perpendicular distance from channel bottom

ν = kinematic viscosity

V_f = shear velocity = $\sqrt{g\ R_H\ S}$ for open channels

R_H = hydraulic radius

S = channel slope

$g = 32.2 \frac{ft}{sec^2}$ = gravitational constant

The above equation is found to change by a constant factor when polymer is injected into the flow. Thus, it is seen that Equation (4) becomes:

$$\frac{v}{V_f} = 5.75 \log \frac{9_y V_f}{\nu} + \Delta B$$

where: ΔB is a function of polymer additive properties and the wall shear stress.